VYSOKÁ ŠKOLA BÁŇSKÁ -
TECHNICKÁ UNIVERZITA OSTRAVA
Hornicko-geologická fakulta

ANALYSIS OF FACTORS INFLUENCING RAINFALL-RUNOFF CONDITIONS

Bakalářská práce

Autor: Marina Alejandra Rodríguez

Vedoucí bakalářské práce: Doc. Ing. Rapantová Naďa, CSc.

Ostrava 2011

PROHLÁŠENÍ

- *Celou bakalářskou práci včetně příloh, jsem vypracoval(a) samostatně a uvedl(a) jsem všechny použité podklady a literaturu.*
- *Byl(a) jsem byl seznámen(a) s tím, že na moji bakalářskou práci se plně vztahuje zákon č.121/2000 Sb. - autorský zákon, zejména § 35 – využití díla v rámci občanských a náboženských obřadů, v rámci školních představení a využití díla školního a § 60 – školní dílo.*
- *Beru na vědomí, že Vysoká škola báňská – Technická univerzita Ostrava (dále jen VŠB-TUO) má právo nevýdělečně, ke své vnitřní potřebě, bakalářskou práci užít (§ 35 odst. 3).*
- *Souhlasím s tím, že jeden výtisk bakalářské práce bude uložen v Ústřední knihovně VŠB-TUO k prezenčnímu nahlédnutí a jeden výtisk bude uložen u vedoucího bakalářské práce. Souhlasím s tím, že údaje o bakalářské práci, obsažené v Záznamu o závěrečné práci, umístěném v příloze mé bakalářské práce, budou zveřejněny v informačním systému VŠB-TUO.*
- *Bylo sjednáno, že s VŠB-TUO, v případě zájmu o komerční využití z její strany, uzavřu licenční smlouvu s oprávněním užít dílo v rozsahu § 12 odst. 4 autorského zákona.*
- *Bylo sjednáno, že užít své dílo – bakalářskou práci nebo poskytnout licenci k jejímu komerčnímu využití mohu jen se souhlasem VŠB-TUO, která je oprávněna v takovém případě ode mne požadovat přiměřený příspěvek na úhradu nákladů, které byly VŠB-TUO na vytvoření díla vynaloženy (až do jejich skutečné výše).*

V Ostravě dne

Marina Alejandra Guadalupe Rodríguez González

SUMMARY

This thesis treats of an overview of the relationship between rainfall and runoff; the main factors that influence in their behavior. At first it will explain how works each process of the hydrological cycle starting with evapotranspiration specifying the difference between evaporation and transpiration. Afterwards an overview of precipitation and its differents forms that fall on the Earth, such as snow, rain, hail, drizzle and sleet; also the static influences on precipitation distribution (altitud, aspect, slope). Subsequently an overview of the rainfall process, its partitions when falls on the ground and its characteristics (volumen, frequency and duration). Further there are explain the terms storage, saturated and unsaturated zone, infiltration and aquifer. At the end of the thesis there is an overview of the runoff process, the runoff mechanism, the three basic flow types, the climatic and physiographic factors affecting runoff and the conclusions of the factors affecting rainfall – runoff processes.

Keywords: evapotranspiration, precipitation, storage, rainfall, runoff.

CONTENTS

1. INTRODUCTION

El Salvador is tropical country situated in the border of the Pacific Ocean, also is the smallest country in Central America but this does not save it from earthquakes caused by hundreds of faults that cross it and also from the climatic problems that cause floods, landslides, damage in the roads and infrastructure, crop losses, and deterioration to the Salvadoran economy.

The rainy season in El Salvador lasts from May until mid-October. The saturation of moisture in soils is caused by the intense storms generated in this country, even though the rainy season is short. Usually, at the first rains, the soil is saturated with water very quickly, generating surface runoff that flows into rivers, lakes and carrying out with it everything, like dirt and garbage. Every year is the same problem; contaminated rivers and lakes; flooding, infrastructure damage, loss of crops, mainly beans, corn and buckwheat and these grains are part of the daily diet of most Salvadorans that live in high risk areas and are economically disadvantaged.

This bachelor thesis tries to explain the relationships between the processes of hydrological cycle, such as evaporation, precipitation, storage and runoff; also it will be explained which are the factors that most affect every process; for example, in the case of runoff, an affecting factor is type of soil, because depending on it, so will be the rate of infiltration in the ground.

2. HYDROLOGIC CYCLE

Water on earth exists in a space called the hydrosphere which extends about 15 km up into the atmosphere and about 1 km down into the lithosphere, the crust of the Earth [1].

Water occurs on the Earth in all its three states, viz. liquid, solid and gaseous, and in various degrees of motion. Evaporation of water from water bodies such as oceans and lakes, formation and movement of clouds, rain and snowfall, streamflow and groundwater movement are some examples of the dynamic aspects of water. The various aspects of water related to the Earth can be explained in terms of a *cycle* known as *"the hydrologic cycle"* [2].

The hydrologic cycle is the central focus of hydrology. The cycle has no beginning or end, and its many processes occur continuously. As shown schematically in Fig. 1, *water evaporates* from the oceans and the land surface to become part of the atmosphere; water vapor is transported and lifted in the atmosphere until it condenses and *precipitates* on the land or the oceans; precipitated water may be *intercepted* by vegetation, become *overland flow* over the ground surface, *infiltrate* into the ground, flow through the soil as *subsurface flow*, and discharge into streams as *surface runoff* [1]. Once it enters a stream channel, runoff becomes *streamflow* [2]. Much of the intercepted water and surface runoff returns to the atmosphere through evaporation. The infiltrated water may percolate deeper to *recharge* groundwater, later emerging in springs or seeping into streams to form surface runoff, and finally flowing out to the sea or evaporating into the atmosphere as the hydrologic cycle continues [1].
Each path of the hydrologic cycle involves one or more of the following aspects:

- transportation of water,
- temporary storage.
- change of state.

For example:

a) the process of rainfall has the change of state and transportation.
b) the groundwater path has storage and transportation aspects.

It can be seen in Table 1 that the main components of the hydrologic cycle can be broadly classified as *transportation (flow) components* and *storage components* [2].

TRANSPORTATION COMPONENTS	STORAGE COMPONENTS
Precipitation	Storage on the land surface (Depression storage, Ponds, Lakes, Reservoirs, etc)
Evaporation	Soil moisture storage
Transpiration	Groundwater storage
Infiltration	
Runoff	

Table 1 Main components of the Hydrologic Cycle [2].

Schematically the interdependency of the transportation components can be represented as in Figure 2. The quantities of water going through various individual paths of the hydrological cycle in a given system can be described by the continuity principle known as *water budget equation* or *hydrologic equation*. It is most important to note that the total water resources of the earth are constant and the sun is the source of energy for the hydrologic cycle. Recognition of the various processes such as evaporation, precipitation and groundwater flow helps us to study the science of hydrology in a systematic way. Also, we realize that man can interfere with virtually any part of the hydrologic cycle, e.g. through artificial rain, evaporation suppression, change of vegetal cover and land use, extraction of groundwater, etc. Interface at one stage can cause serious repercussions at some other stage of the cycle. The hydrological cycle has important influences in a variety of fields including agriculture, forestry, geography, economics, sociology and political scene [2].

Quantitative data of the total amount of water on the Earth and in the various processes of the hydrologic cycle are scarce, particularly over the oceans, and so the amounts of water in the various components of the global hydrologic cycle are still not known precisely [1]. Table 2 lists estimated quantities of water in various forms on the earth. About 96.5 percent of all the earth's water is in the oceans. If the earth were a uniform sphere, this quantity would be sufficient to cover it to a depth of about 2.6 km. Of the remainder, 1.7

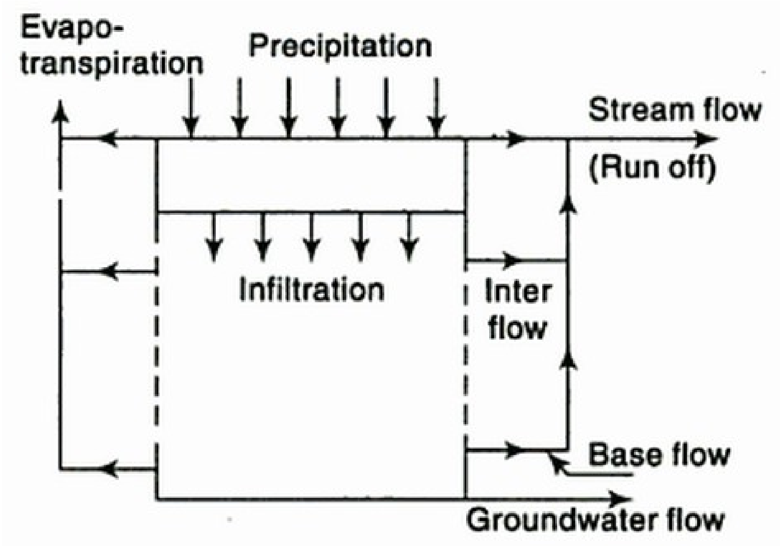


Figure 2 Transportation components of the Hydrologic Cycle [2].

percent is in the polar ice, 1.7 percent in groundwater and only 0.1 percent in the surface and atmospheric water systems. The atmospheric water system, the driving force of surface water hydrology, contains only 12,900 km^3 of water, or less than one part in 100,000 of all the earth's water. Of the earth's fresh water, about two-thirds is polar ice and most of the remainder is groundwater going down to a depth of 200 to 600 m. Most groundwater is saline below this depth. Only 0.006 percent of fresh water is contained in rivers. Biological water, fixed in the tissues of plants and animals, makes up about 0.003 percent of all fresh water, equivalent to half the volume contained in rivers [1].

Although the water content of the surface and atmospheric water systems is relatively small at any given moment, immense quantities of water annually pass through them. The global annual water balance is shown in Table 3. Figure 2 shows the major components in units relative to an annual land precipitation volume of 100. It can be seen that evaporation from the land surface consumes 61 percent of this precipitation, the remaining 39 percent forming runoff to the oceans, mostly as surface water. Evaporation from the oceans contributes nearly 90 percent of atmospheric moisture. Analysis of the flow and storage of water in the global water balance provides some insight into the dynamics of the hydrologic cycle [1].

Item	Area (10^6 km^2)	Volume (km^3)	Percent of total water	Percent of fresh water
Oceans	361.30	1338000,000.00	96.5000	
Groundwater				
Fresh	134.80	10530,000.00	0.7600	30.100
Saline	134.80	12870,000.00	0.9300	
Soil Moisture	82.00	16,500.00	0.0012	0.050
Polar ice	16.00	24023,500.00	1.7000	68.600
Other ice and snow	0.30	340,600.00	0.0250	1.000
Lakes				
Fresh	1.20	91,000.00	0.0070	0.260
Saline	0.80	85,400.00	0.0060	
Marshes	2.70	11,470.00	0.0008	0.030
Rivers	148.80	2,120.00	0.0002	0.006
Biological water	510.00	1,120.00	0.0001	0.003
Atmospheric water	510.00	12,900.00	0.0010	0.040
Total water	510.00	1385984,610.00	100.0000	
Freshwater	148.80	35029,210.00	2.5000	100.000

Table 2 Estimated World Water Quantities [1].

Although the concept of the hydrologic cycle is simple, the phenomenon is enormously complex and intricate. It is not just one large cycle but rather is composed of many interrelated cycles of continental, regional, and local extent. Although the total volume of water in the global hydrologic cycle remains essentially constant, the distribution of this water is continually changing on continents, in regions, and within local drainage basins [1].

2.1. The water balance equation

The hydrological cycle is a conceptual model representing our understanding of which processes are operating within an overall earth–atmosphere system. To represent this it is use an equation termed the water balance equation, is a mathematical description of the hydrological processes operating within a given timeframe and incorporates principles of mass and energy continuity. In this way the hydrological cycle is defined as a closed system whereby there is no mass or energy created or lost within it. The mass of concern in this case is water. There are numerous ways of representing the water balance equation but equation 1.1 shows in it its most fundamental form [3].

$$P \pm E \pm \Delta S \pm Q = 0 \tag{1}$$

where P is precipitation; E is evaporation; ΔS is the change in storage and Q is runoff. *Precipitation* in the water balance equation represents the main input of water to a surface (e.g. a catchment). *Evaporation* is a mixture of open water evaporation (i.e. from rivers and lakes); the soil surface and vegetation (including both *interception* and *transpiration* from plants). The *storage* term includes soil moisture, deep groundwater, water in lakes, glaciers, seasonal snow cover. The broad term *runoff* incorporates the movement of liquid water above and below the surface of the earth. The movement of water below the surface necessitates an understanding of infiltration into the soil and how the water moves in the unsaturated zone (*throughflow*) and in the saturated zone (*groundwater flow*) [3].

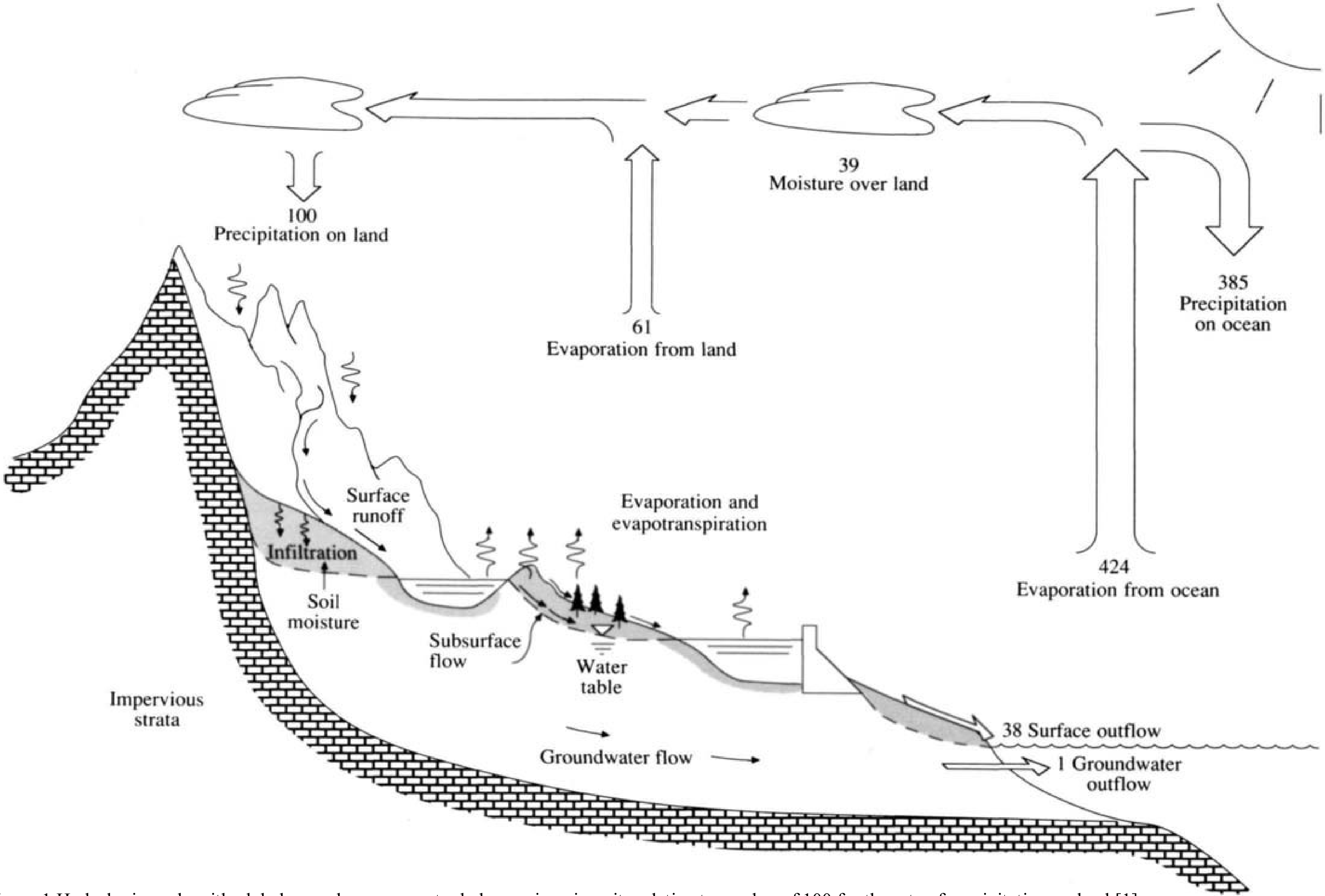


Figure 1 Hydrologic cycle with global annual average water balance given in units relative to a value of 100 for the rate of precipitation on land [1].

		Ocean	Land
Area (km^2)		361,300,000	148,800,000
Precipitation	(km^3/yr)	458,000	119,000
	(mm/yr)	1270	800
	(in/yr)	50	31
Evaporation	(km^3/yr)	505,000	72,000
	(mm/yr)	1400	484
	(in/yr)	55	19
Runoff to ocean			
Rivers	(km^3/yr)	-	44,700
Groundwater	(km^3/yr)	-	2200
Total runoff	(km^3/yr)	-	47,000
	(mm/yr)	-	316
	(in/yr)	-	12

Table 3 Global annual water balances [1].

3. EVAPOTRANSPIRATION

3.1. Evaporation

Under the concept *evaporation* we understand the process by which water is converted from its liquid state to its gaseous state and thus it is transferred from land and water masses to the atmosphere.

It occurs on water, snow, soil, and vegetation surfaces. When the loss of water occurs on an open water (lakes, rivers, reservoirs) and soil surfaces it is called *evaporation*, when occurs on vegetation surfaces *transpiration* and *evapotranspiration* it is referred as the total loss of water in vapor state. Evaporation as a process requires an energy source, an available water supply to transform liquid water into water vapour, and one more condition, that the atmosphere be dry enough to receive any water vapour produced. These are the three fundamental parts to an understanding of the evaporation process. The English physicist Dalton (1766 – 1844), was the first to understand the evaporation process, so, he linked wind speed and the dryness of the air to evaporation rate [3].

The higher the wind speed and the temperature are, the more evaporation; and the lower the humidity is, the more evaporation, this it will be explained bellow in chapter number 3.4.

The main source of energy for evaporation is from the sun. This is not necessarily in the form of direct radiation, it is often absorbed by a surface and then re-radiated at a different wavelength. The normal term used to describe the amount of energy received at a surface is net radiation [3]. Above absolute zero, water molecules are active and move in different directions. Some move from the water surface to the air and some jump from air into water. The net loss of water molecules of the water is *evaporation*; the net gain of water molecules is *condensation*, while the equilibrium between air and water is *saturation* [4].

3.2. Transpiration

Transpiration is the process where water contained in liquid form in plants is converted to vapor and released to the atmosphere. Much of the water taken up by plants is released through transpiration [5]. Transpiration from a plant occurs as part of photosynthesis and respiration [3]. Water is drawn into a plant rootlet from the soil moisture owing to osmotic pressure, whereupon it moves through the plant to the leaves. The turgidity of non woody vascular plants is caused by the cellular pressures of the contained water. The water is passed as vapor through openings in the surface of the leaves known as stomata. Air also passes through these openings. A small portion (less than 1%) of the water is used to manufacture plant tissue, but most is transpired to the atmosphere. The process of transpiration accounts for most of the vapor losses from a land dominated drainage basin. The amount of transpiration is a function of the density and size of the vegetation [6].

The value of transpiration varies according to the type of vegetation, its ability to transpire and to the availability of water in the soil [7].

3.3. Evapotranspiration

As it was explained, *evapotranspiration* is the combination of evaporation from the soil surface and transpiration from vegetation. The same factors governing open water evaporation also govern evapotranspiration, namely energy supply and vapor transport. In addition, a third factor enters the picture: the supply of moisture at the evaporative surface. As the soil dries out, the rate of evapotranspiration drops below the level it would have maintained in a well watered soil [1].

3.4. Factors affecting evapotranspiration

At the beginning of the chapter two, it has been said that for the process of evaporation as well as transpiration it is necessary a source of energy and this is provided by energy from the Sun. The latent heat of evaporation comes from solar (short-wave) and terrestrial (long-wave) radiation. The incoming *solar radiation* is the dominant source of heat and affects evaporation amounts over the surface of the Earth according to latitude and season [7].

Temperature of both air and the evaporating surface is important and is also dependent on the major energy source, the Sun. The higher the air temperature, the more water vapour it can hold, and similarly, if the temperature of the evaporating water is high, it can more readily vaporize. Thus evaporation amounts are high in tropical climates and tend to be low in Polar Regions. Similar contrasts are found between summer and winter evaporation quantities in mid-latitudes [7].

Directly related to temperature is the *water vapour capacity of the air.* A measure of the amount of water vapour in the air is given by the vapour pressure, and a unique relationship exists between the saturated vapour pressure and the air temperature (Fig. 3). Evaporation is dependent on the saturation deficit of the air, which is the amount of water vapour that can be taken up by the air before it becomes saturated. The saturation deficit is given by the difference between the saturation vapour pressure at the air temperature and the actual vapour pressure of the air. Hence more evaporation occurs in inland areas where the air tends to be drier than in coastal regions with damp air from the sea [7].

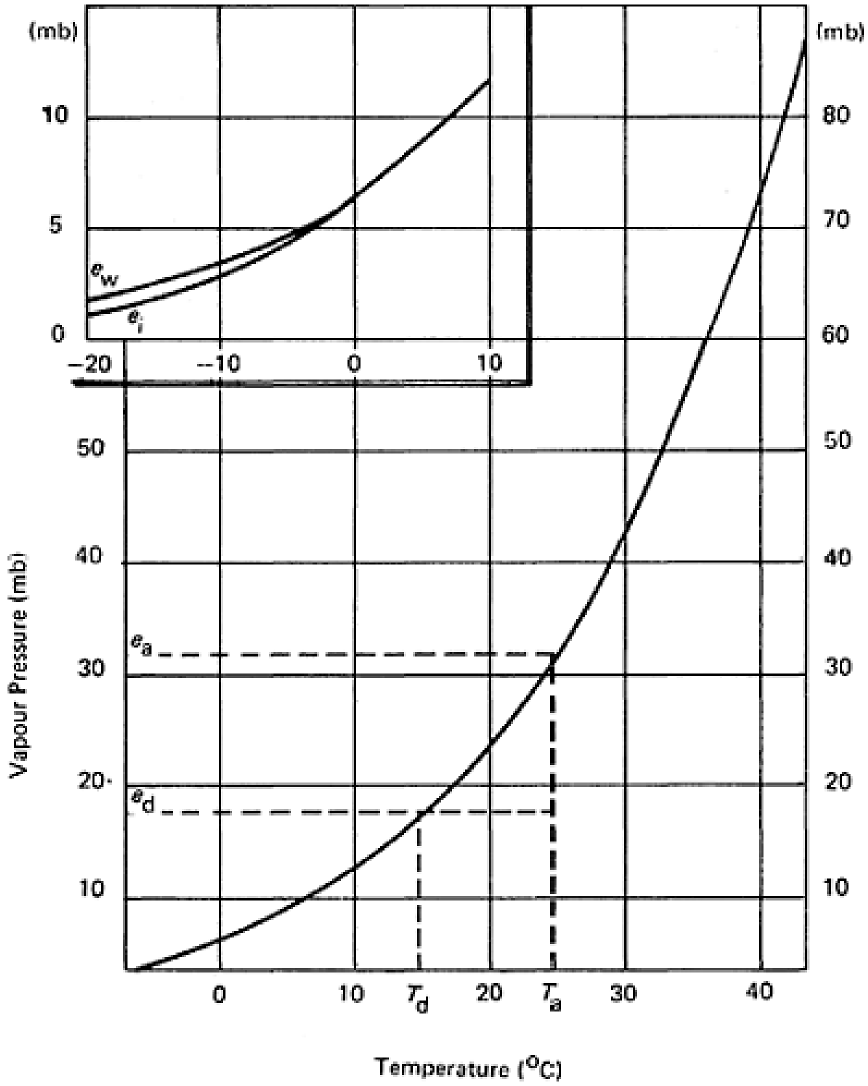


Figure 3 Saturation pressure and air temperature $e_a – e_d$ = saturation deficit.
T_d=dew point temperature [7].

As water evaporates, the air above the evaporating surface gradually becomes more humid until finally it is saturated and can hold no more vapour. If the air is moving, however, the amount of evaporation is increased as drier air replaces the humid air. Thus *wind speed* at the surface is an important factor. Evaporation is greater in exposed areas that enjoy plenty of air movement than in sheltered localities where air tends to stagnate [7].

The best indicator of atmospheric mixing is the *wind speed* at different heights above an evaporating surface. If the *wind speed* is zero the parcel of air will not move away from the evaporative surface and will „fill" with water vapour. As the wind speed increases, the parcel of air will be moved quickly on to be replaced by another, possibly drier, parcel ready to absorb more water vapour. If the evaporative surface is large (e.g. a lake) it is important that the parcel of air moves up into the atmosphere, rather than directly along at the same level, so that there is drier air replacing it. This occurs through turbulent diffusion of the air. There is a greater turbulence associated with air passing over a rough surface than a smooth one, something that will be returned to in the discussion of evaporation estimation [3].

It will be noted that the *temperature* and *wind speed* factors may be in conflict in affecting evaporation since windy areas tend to be cooler and sheltered areas are often warmer. Over a large catchment area, it is the general characteristics of the prevailing air mass that will have the major affect on evaporation (apart from the direct solar radiation). The principle influences on the physical process of evaporation enumerated above are in their turn affected by wider considerations. The following factors outline more generally larger-scale influences [7].

The prevailing weather pattern indicated by the *atmospheric pressure* affects evaporation. The edge of an anticyclone provides ideal conditions for evaporation as long as some air movement is operating in conjunction with the high air pressure. Low atmospheric pressure usually has associated with it damp unsettled weather in which the air is already well charged with water vapour and conditions are not conducive to id evaporation [7].

The nature of the *evaporating surface* affects evaporation by modifying the wind pattern. Over a rough, irregular surface, friction reduces wind speed but has a tendency to cause turbulence so, with an induced vertical component in the wind, evaporation is enhanced. Over an open water surface, strong winds cause waves which provide an increased surface for evaporation in addition to causing turbulence. As wind passes over smooth, even surfaces there is little friction and turbulence and the evaporation is affected predominantly by the horizontal velocity [7].

Variations in some of the dominant factors operating over different surfaces can result in noticeable changes in evaporation rates over small adjacent areas in short time periods. Diurnal fluctuations are considerable since during the night there is no solar radiation. Evaporation is necessarily dependent on a supply of water and thus the availability of moisture is a crucial factor. With all the other factors acting favorably, once the body of water disappears then open water evaporation ceases. For transpiration, the availability of water is not so easily observed. Plants draw their supply from the soil where the moisture is held under tension, and their rate of transpiration is governed by the stomata in the leaves which act like valves to regulate the passage of water through the pores according to the incidence of light. The pores are closed in darkness and hence transpiration ceases at night. When there is a shortage of water in the soil, the stomata regulate the pores and reduce transpiration. Thus transpiration is controlled by soil moisture content and the capacity of the plants to transpire, which are conditioned by the meteorological factors [7].

If there is a continuous supply and the rate of evaporation is unaffected by lack of water, then both evaporation and transpiration are regulated by the meteorological variables, *viz* radiation, temperature, vapour pressure and wind speed [7].

3.5. Evaporation over a vegetation canopy

Where there is a vegetation canopy the evaporation above this surface will be a mixture of transpiration, evaporation from the soil and evaporation from wet leaves *(canopy interception or interception loss or wet leaf evaporation)*. The relative importance of these three evaporation sources will depend on the degree of vegetation cover and the climate at the site. In tropical rain forests transpiration is the dominant water loss but where there is a seasonal soil water deficit the influence of canopy interception loss becomes more important [3].

It is the role of interception loss (wet leaf evaporation) that makes afforested areas greater users of water than pasture land. This is because the transpiration rates are similar between pasture and forest but the interception loss is far greater from a forested area. There are two influences on the amount of interception loss from a particular site: *canopy structure and meteorology* [3].

Canopy *structural factors* include the *storage* capacity, the *drainage* characteristics of the canopy and the *aerodynamic* roughness of the canopy. The morphology of leaf and bark on a tree are important factors in controlling how quickly water *drains* towards the soil. If leaves are pointed upwards then there tends to be a rapid drainage of water towards the stem. Sometimes this appears as an evolutionary strategy by a plant in order to harvest as much water as possible (e.g. rhubarb and gunnera plants). Large broadleaved plants, such as oak (Quercus), tend to hold water well on their leaves while needled plants can hold less per leaf (although they normally have more leaves). Seasonal changes make a large difference within deciduous forests, with far greater interception losses when the trees have leaves than without. The *aerodynamic* roughness of the canopy means that as air passes over the canopy it creates a turbulent flow that is very effective at moving evaporated water away from the surface. The reason that forests have such high interception losses is because they have a lot of intercepting surfaces and they have a high aerodynamic roughness leading to high rates of diffusion of the evaporated water away from the leaf [3].

Meteorological factors affecting the amount of interception loss are the rainfall characteristics. The rate at which rainfall occurs (intensity) and storm duration are critical in controlling the interception loss. The longer water stays on the canopy the greater the amount of interception loss [3]. In later chapters it will be taken these characteristics more deeply.

4. PRECIPITATION

Precipitation is the release of water from the atmosphere to reach the surface of the earth. The term “precipitation” covers all forms of water being released by the atmosphere, including snow, hail, sleet and rainfall. It is the major input of water to a river catchment area and as such needs careful assessment in any hydrological study. Although rainfall is relatively straightforward to measure it is notoriously difficult to measure accurately and, to compound the problem, is also extremely variable within a catchment area [3].

4.1. Precipitation formation

The ability of air to hold water vapour is temperature dependent: the cooler the air the less water vapour is retained. If a body of warm, moist air is cooled then it will become saturated with water vapour and eventually the water vapour will condense into liquid or solid water (i.e. water or ice droplets). The water will not condense spontaneously however; there need to be minute particles present in the atmosphere, called *condensation nuclei*, upon which the water or ice droplets form. The water or ice droplets that form on condensation nuclei are normally too small to fall to the surface as precipitation; they need to grow in order to have enough mass to overcome uplifting forces within a cloud [3].

For precipitation to occur, there are three conditions that have to be met previous to precipitation forming [6]:

- A humid air mass must be cooled to the dew-point temperature, *cooling mechanism.*
- Condensation or freezing nuclei must be present, *condensation nuclei*.
- Droplets must coalesce to form raindrops, and raindrops must be of sufficient size when they leave the clouds to ensure that they will not totally evaporate before they reach the ground, *water droplet growth* [6].

The formation of precipitation in clouds is illustrated in Figure 4 [1].

4.1.1. Cooling mechanism

Air temperature can be cooled down due to one or more of the following causes:

- Adiabatic cooling due to convective heating or orographic lifting
- Frontal cooling due to mixing of two air masses different in temperature
- Contact cooling due to a colder surface
- Radiation cooling due to the loss of heat at the ground surface [4].

Process known as *adiabatic expansion*, occurs when the air mass rises in the atmosphere. Since the atmosphere becomes less dense with altitude, a rising air mass must expand owing to the lower pressure. If no exchange of heat occurs between the air mass and its surroundings, the laws of thermodynamics dictate that the temperature will fall. When the air mass reaches the dew-point temperature, further lifting and cooling will cause condensation and the latent heat of vaporization is released [6].

Cooling of the atmosphere may take place through several different mechanisms occurring independently or simultaneously. The most common form of cooling is from the uplift of air through the atmosphere. As air rises the pressure decreases; Boyle's Law states that this will lead to a corresponding cooling in temperature. The cooler temperature leads to less water vapour being retained by the air and conditions becoming favorable for condensation. The actual uplift of air may be caused by heating from the earth's surface (leading to convective precipitation), an air mass being forced to rise over an obstruction such as a mountain range (this leads to orographic precipitation), or from a low pressure weather system where the air is constantly being forced upwards (this leads to cyclonic precipitation). Other mechanisms whereby the atmosphere cools include a warm air mass meeting a cooler air mass, and the warm air meeting a cooler object such as the sea or land [3].

4.1.1. Condensation nuclei

Condensation nuclei, as was explained before, are minute particles floating in the atmosphere which provide a surface for the water vapour to condense into liquid water upon. They are commonly less than a micron (i.e. one millionth of a meter) in diameter. There are many different substances that make condensation nuclei, including small dust particles, sea salts and smoke particles [3].

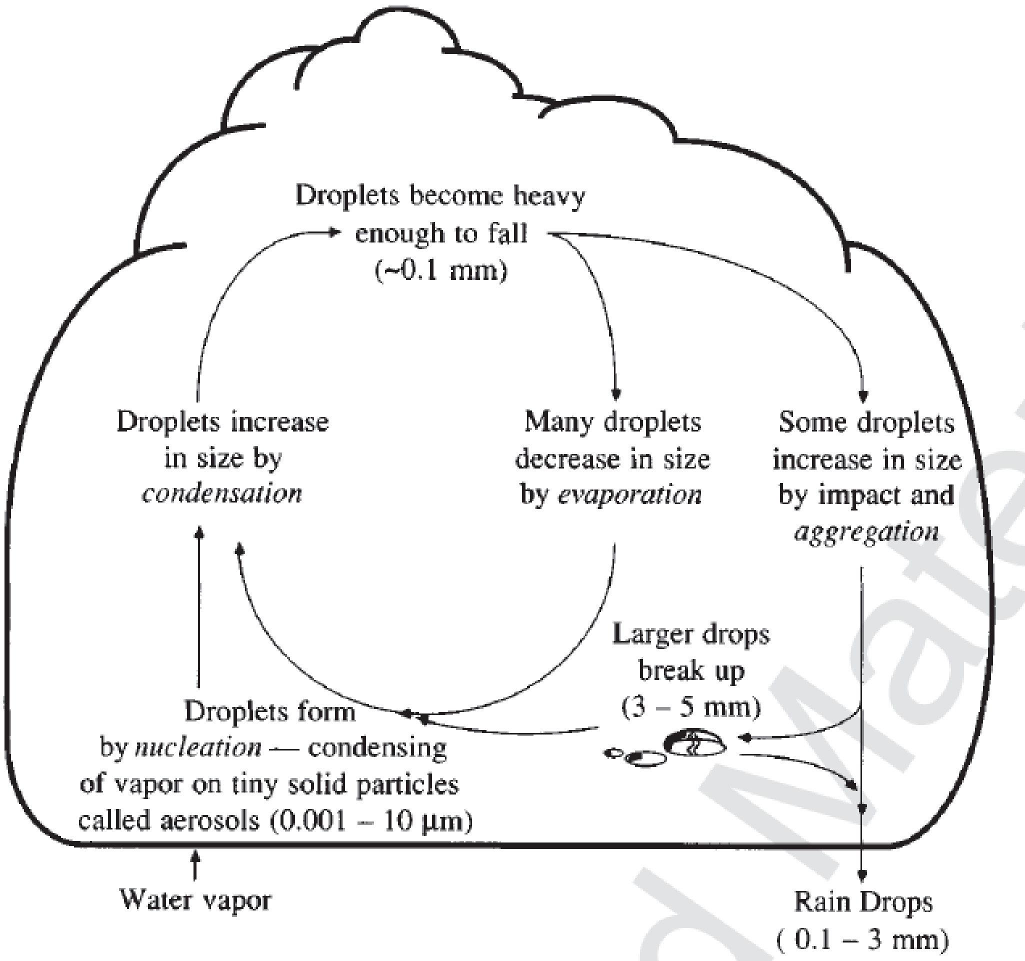


Figure 4 The formation of precipitation in clouds.
Water droplets in clouds are formed by nucleation of vapor on aerosols, then go through many condensation-evaporation cycles as they circulate in the cloud, until they aggregate into large enough drops to fall through the cloud base [1].

4.1.2. Water droplet growth

Water or ice droplets formed around condensation nuclei are normally too small to fall directly to the ground; that is, the forces from the upward draught within a cloud are greater than the gravitational forces pulling the microscopic droplet downwards. In order to overcome the upward draughts it is necessary for the droplets to grow from an initial size of 1 micron to around 3,000 microns (3 mm). The vapour pressure difference between a droplet and the surrounding air will cause it to grow through condensation, albeit rather slowly. When the water droplet is ice the vapour pressure difference with the surrounding air becomes greater and the water vapour sublimates onto the ice droplet. This will create a precipitation droplet faster than condensation onto a water droplet, but is still a slow process. The main mechanism by which raindrops grow within a cloud is through *collision and coalescence*. Two raindrops collide and join together (coalesce) to form a larger droplet that may then collide with many more before falling towards the surface as rainfall or another form of precipitation [3].

Another mechanism leading to increased water droplet size is the so-called Bergeron process. The pressure exerted within the parcel of air, by having the water vapour present within it, is called the vapour pressure. The more water vapour present the greater the vapour pressure. Because there is a maximum amount of water vapour that can be held by the parcel of air there is also a maximum vapour pressure, the so-called saturation vapour pressure. The saturation vapour pressure is greater over a water droplet than an ice droplet because it is easier for water molecules to escape from the surface of a liquid than a solid. This creates a water vapour gradient between water droplets and ice crystals so that water vapour moves from the water droplets to the ice crystals, thereby increasing the size of the ice crystals. Because clouds are usually a mixture of water vapour, water droplets and ice crystals, the Bergeron process may be a significant factor in making water droplets large enough to become rain drops (or ice/snow crystals) that overcome gravity and fall out of the clouds. The mechanisms of droplet formation within a cloud are not completely understood. The relative proportion of condensation-formed, collision-formed, and Bergeron-process-formed droplets depends very much on the individual cloud circumstances and can vary considerably. As a droplet is moved around a cloud it may freeze and thaw several times, leading to different types of precipitation like it shows table 4 [3].

Class	Definition
Rain	Liquid water droplets between 0.5 and 7 mm in diameter
Drizzle	A subset of rain with droplets less than 0.5 mm
Sleet	Freezing raindrops; a combination of snow and rain
Snow	Complex ice crystals agglomerated
Hail	Balls of ice between 5 and 125 mm in diameter

Table 4 Classes of precipitation used by the UK Meteorological Office [3].

4.2. Moisture convergence

Water-vapor content in the atmosphere is about 25 mm at any given time. Thus, additional water must be supplied from the surrounding areas dominated with high pressure to the stormy areas dominated with low pressure in order for a storm to remain at a constant rate or even increase during a storm system. The *greater* the *atmospheric pressure* gradient between the high and low pressure areas, the *greater* the storm intensity [4].

4.3. Dewfall

The same process of condensation occurs in dewfall, only in this case the water vapour condenses into liquid water after coming into contact with a cold surface. In humid-temperate countries dew is a common occurrence in autumn when the air at night is still warm but vegetation and other surfaces have cooled to the point where water vapour coming into contact with them condenses onto the leaves and forms dew. Dew is not normally a major part of the hydrological cycle but is another form of precipitation [3].

4.4. Weather systems for precipitation

Precipitation is often categorized into three types in accordance with cooling mechanisms that generate vertical lifting and formation of precipitation [4].

4.4.1. Orographic precipitation

When an air mass is lifted up mechanically by mountain barriers, the reduced atmospheric pressure at higher elevations causes cooling and condensation by expansion. It results in greater precipitation. Thus, precipitation is greater at higher elevations on the windward slope of mountainous areas [4].

4.4.2. Convective precipitation

Unequal heating between different surfaces, such as plowed field vs. forest or land vs. water, or the increase of water vapor content in the air due to evapotranspiration in hot summer afternoons, can make air unstable. Heated air over the hot surface expands, becomes lighter, and begins to rise. The unstable air continues to rise and is replaced by cool air from the surroundings. This can cause pronounced vertical movements, adiabatic cooling, condensation, and precipitation. Convective storms are spotty with intensity ranging from light to cloudbursts (100 mm/h or more) [4].

Depending upon the moisture, thermal and other conditions light showers to thunderstorms can be expected in convective precipitation. Usually the areal extent of such rains is small, being limited to a diameter of about 10 km [1].

4.4.3. Cyclonic precipitation

Cyclonic precipitation can cover a large area over a long duration. It can be either frontal or nonfrontal. Fronts are boundaries that separate masses of air having significantly different physical properties in humidity, temperature, pressure, and motion. If the moving warm air masses are pushed upward by a cold air mass, it is a cold front. If the cold air retreats, warm air pushing over it produces a warm front. When the boundary does not move, the front becomes stationary. Fronts usually bring bad weather. Cold fronts usually move faster, the frontal surfaces are steeper, their upward movements are more rapid, and precipitation rates are much greater than those of warm fronts. Nonfrontal precipitation results from air lifting through horizontal convergence of the inflow from high-pressure areas into low-pressure areas. The precipitation types mentioned above can have intensity from near zero to over 100 mm/h [4].

A *cyclone* is a large low pressure region with circular wind motion. Two types of cyclones are recognized: tropical cyclones and extratropical cyclones [1].

a) Tropical cyclone

A tropical cyclone, also called *cyclone* in India, *hurricane* in USA and *typhoon* in South-East Asia, is a wind system with an intensely strong depression with MSL pressures sometimes below 915 mbar. The normal areal extent of a cyclone is about 100 – 200 km in diameter [1].

b) Extratropical Cyclone

These are cyclones formed in locations outside the tropical zone. Assoiated with a frontal system, they possess a strong counter-clockwise wind circulation in the northern hemisphere. The magnitude of precipitation and wind velocities are relatively lower than those of a tropical cyclone. However, the duration of precipitation is usually longer and the areal extent is larger also [1].

4.5. Precipitation Distribution

The amount of precipitation falling over a location varies both spatially and temporally (with time). The different influences on the precipitation can be divided into static and dynamic influences. Static influences are those such as altitude, aspect and slope; they do not vary between storm events. Dynamic influences are those that do change and are by and large caused by variations in the weather. At the global scale the influences on precipitation distribution are mainly dynamic being caused by differing weather patterns, but there are static factors such as topography that can also cause major variations through a *rain shadow effect*. At the continental scale large differences in rainfall can be attributed to a mixture of static and dynamic factors [3].

4.5.1. Static influences on precipitation distribution

It is easier for the hydrologist to account for static variables such as those discussed below.

a) Altitude

Temperature is a critical factor in controlling the amount of water vapour that can be held by air. The cooler the air is, the less water vapour can be held. As temperature decreases with altitude it is reasonable to assume that as an air parcel gains altitude it is more likely to release the water vapour and cause higher rainfall. As we explain in "Orographic precipitation", there is a strong correlation between altitude and rainfall: so-called *orographic precipitation* [3].

b) Aspect

The influence of aspect is less important than altitude but it may still play an important part in the distribution of precipitation throughout a catchment. In the humid mid-latitudes (35° to 65° north or south of the equator) the predominant source of rainfall is through cyclonic weather systems arriving from the west. The slopes within a catchment that face eastwards will naturally be more sheltered from the rain than those facing westwards. The same principle applies everywhere: slopes with aspects facing away from the predominant weather patterns will receive less rainfall than their opposites [3].

c) Slope

The influence of slope is only relevant at a very small scale. Unfortunately the measurement of rainfall occurs at a very small scale (i.e. a rain gauge). The difference between levels rain gauge on a hillslope, compared to one parallel to the slope, may be significant. It is possible to calculate this difference if it is assumed that rain falls vertically – but of course rain does not always fall vertically. Consequently the effect of slope on rainfall measurements is normally ignored [3].

Precipitation variability for the world is shown in Fig. 5. The average annual precipitation on the land surface of the earth is about 1000 mm (40 in), but great variability exists, from Arica, Chile; with an annual average of 0.5 mm (0.02 in) to Mt. Waialeale, Hawaii; which receives 11,680 mm (460 in) per year on average [1].

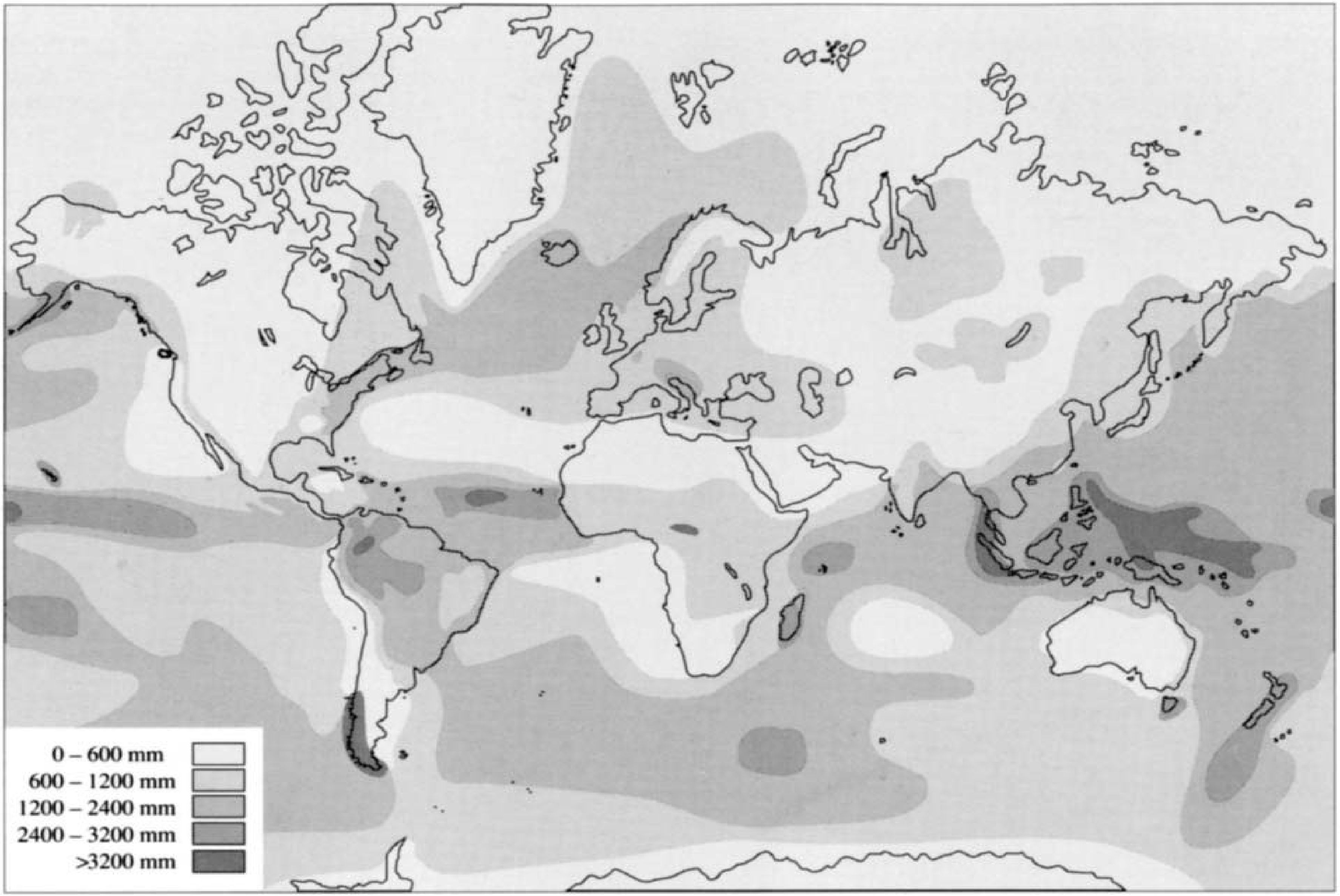


Figure 5 Mean annual precipitation of the world in millimeters (l mm = 0.04 in) [1].

5. RAINFALL

As it was explain in chapter number four the term *rainfall* is used to describe precipitation in the form of water drops of sizes larger than 0.5 mm. [2]. In a tropical country like El Salvador, major portion of the precipitation occurs in the form of *rain* only. That is why in some books *precipitation* and *rainfall* are used synonymously [8].

5.1. Rainfall partitioning

When rain falls onto a vegetation canopy it effectively partitions the water into separate modes of movement: throughfall, stemflow and interception loss. This is illustrated in Figure 6 [3].

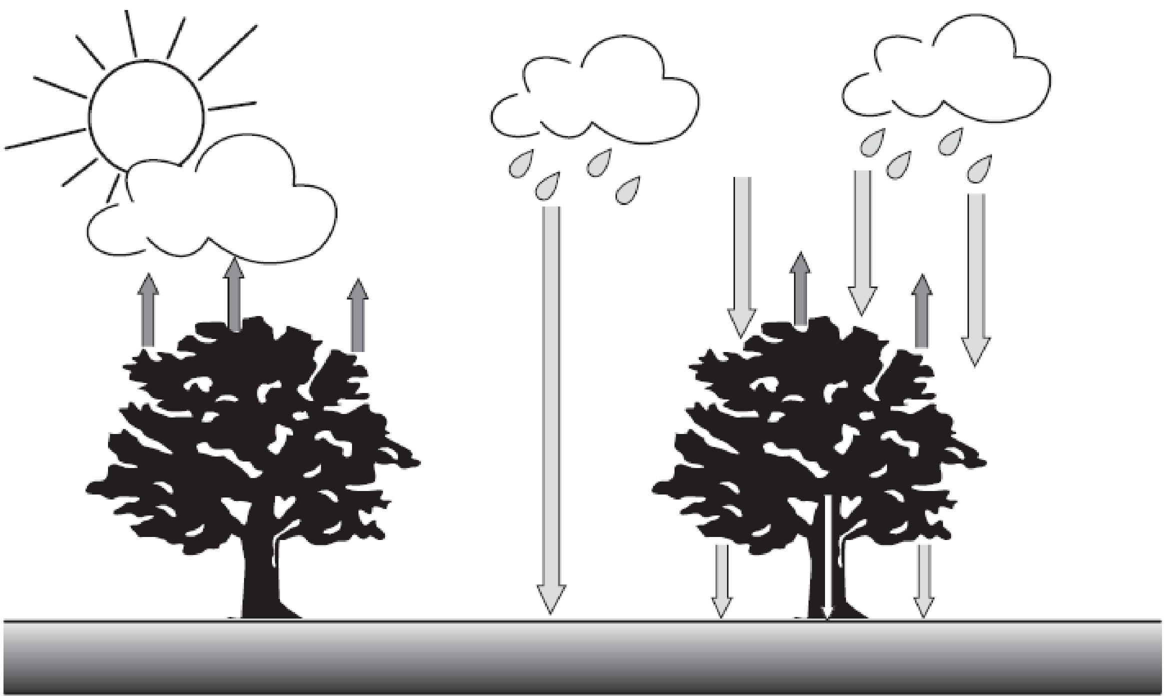


Figure 6 Rainfall above and below a canopy.
Indicated on the diagram are stemflow (white arrow on trunk); direct and indirect throughfall (lightly hatched arrow); and interception loss (upwardfacing darker arrow) [3].

5.1.1. Throughfall

This is the water that falls to the ground either directly, through gaps in the canopy, or indirectly, having dripped off leaves, stems or branches. The amount of direct throughfall is controlled by the canopy coverage for an area, a measure of which is the leaf area index (LAI). LAI is actually the ratio of leaf area to ground surface area and consequently has a value greater than one when there is more than one layer of leaf above the ground. When the LAI is less than one you would expect some direct throughfall to occur. When you shelter under a tree during a rainstorm you are trying to avoid the rainfall and direct throughfall. The greater the surface area of leaves above you, the more likely it is that you will avoid getting wet from direct throughfall. The amount of indirect throughfall is also controlled by the LAI, in addition to the canopy storage capacity and the rainfall characteristics. Canopy storage capacity is the volume of water that can be held by the canopy before water starts dripping as indirect throughfall. The canopy storage capacity is controlled by the size of trees, plus the area and water-holding capacity of individual leaves. Rainfall characteristics are an important control on indirect throughfall as they dictate how quickly the canopy storage capacity is filled. Experience of standing under trees during a rainstorm should tell you that intensive rainfall quickly turns into indirect throughfall, whereas light showers frequently do not reach the ground surface at all. In reality canopy storage capacity is a rather nebulous concept. Canopy characteristics are constantly changing and it is rare for water on a canopy to fill up completely before creating indirect throughfall. This means that indirect throughfall occurs before the amount of rainfall equals the canopy storage capacity, making it difficult to gauge exactly what the storage capacity is [3].

5.1.2. Stemflow

Stemflow is the rainfall that is intercepted by stems and branches and flows down the tree trunk into the soil. Stemflow acts like a funnel, collecting water from a large area of canopy but delivering it to the soil in a much smaller area: the surface of the trunk at the base of a tree [3].

5.1.3. Interception loss

While water sits on the canopy, prior to indirect throughfall or stemflow, it is available for evaporation, referred to as interception loss. This is an evaporation process [3].

5.2. Rainfall characteristics

5.2.1. Volume-Duration-Frequency

Storms differ in a number of characteristics; here it is described three important characteristics [9]:

a) *Volume*: the amount of precipitation occurring over the storm duration

b) *Duration*: the length of time over which a precipitation event occurs

c) *Frequency*: the frequency of occurrence of events having the same volume and duration

Closely related to these definitions is the concept of *intensity*, which equals the volume, divided by the duration [9]. In others words *intensity* of rainfall is the quantity of rain that falls eventually.

In the basis of its intensity, rainfall is classified as [2]:

Type	Intensity
Light rain	Trace to 2.5 mm/h
Moderate rain	2.5 mm/h to 7.5 mm/h
Heavy rain	> 7.5 mm/h

Table 5 Type of rain by its Intensity [2].

a) Relation between Volume and Depth

The volume of a storm is most often reported as a depth, with units of length such as inches or centimeters; in such cases, the depth is assumed to occur uniformly over the watershed. Thus the volume equals the depth times the watershed area. The interchanging use of units for storm volume often leads to confusion because the terms *depth* and *volume* are applied to a quantity having units of length. One might speak of the rainfall volume, but express it in inches. Such statements imply that the depth occurred uniformly over the entire watershed and the units are "area-inches," with the area of the watershed used to compute a volume in acre-inches or some similar set of units. It is also important to recognize the interdependence of these terms. A specified depth of rainfall may occur from many different combinations of *intensities* and *durations*, and these different combinations of intensities and durations will have a significant effect on both runoff volumes and rates. For example, as it shows the next table, three inches of precipitation may result from any of the following combinations of intensity and duration [9]:

Intensity [in/hr]	Duration [hr]	Depth [in]
12	0.25	3
6	0.50	3
3	1.00	3
1.5	2.00	3

Table 6 Depth, Intensity and Duration of a storm [9].

b) Frequency

Just as the others three concepts explain before, frequency is also an important determinant. Frequency can be discussed in terms of either the exceedence probability or the return period, which are defined as follows [9]:

- *Exceedence probability*: the probability that an event having a specified depth and duration will be exceeded in one time period, which is most often assumed to be one year.
- *Return period*: the average length of time between events having the same depth and duration.

The exceedence probability (p) and return period (T) are related by [9]:

$$\boldsymbol{p = \frac{1}{T}} \tag{2}$$

Events having similar intensities may differ significantly in depth and duration when a difference in frequency occurs. For example, the three storms have similar intensities, but differ significantly in depth, duration, and frequency [9]:

Depth [in]	Duration [hr]	Frequency [yr]	Intensity [in/hr]
5.8	8	100	0.78
3.3	4	10	0.82
1.6	2	2	0.80

Table 7 A comparison of depth, duration, frequency and intensity for three different storms [9].

The table illustrates the need to consider the frequency of the event, as well as the depth, intensity, and duration [9].

5.3. Measurement of Rainfall

Precipitation was probably the first hydrological phenomenon to have been record by man. There is evidence that rainfall records were kept in India in the 4th century B. C. All forms of precipitation are essentially measured on the basis of the vertical depth of water that would accumulate on a level surface if the precipitation is retained where it fell. Precipitation is usually measured in millimeters and tenths of millimeters. A small surface area is taken for the purpose of measurement and the volume of precipitation water collected over that area is divided by the area to give the depth of precipitation [8].

The prevailing wind at the time of rainfall would change the trajectory of the falling precipitation from vertical and more will fall on a given area normal to the trajectory than on the same area in a horizontal plane. However, since a catchment area is computed as the projection upon a horizontal plane the gauge with its receiving area in a horizontal plane gives a representative measurement. The precipitation is measured by an instrument called a *rain gauge*. Rain gauge is also variously known as *hyetometer*, *ombrometer* or *pluviometer*. The raingauges are of two types: Non- recording type or ordinary raingauges and Recording types or automatic raingauges [8].

The four main sources of error in measuring rainfall that need consideration in designing a method for the accurate measurement of rainfall are [8]:

- Losses due to evaporation

- Losses due to wetting of the gauge
- Over-measurement due to splash from the surrounding area
- Under-measurement due to turbulence around the gauge

5.4. Representation of rainstorms

Rainstorms can be represented by isohyetal maps; an isohyet is a contour of constant rainfall. Figure 7 shows an isohyetal map of total rainfall depth measured for two storms: one a storm of May 30-June 1, 1889, in Johnstown, Pennsylvania, following a dam failure, and the other a storm of May 24-25, 1981, in Austin, Texas. The maximum depth of precipitation in both storms is nearly the same (~ 10 in), but the Austin storm was briefer and more localized than the Johnstown storm. Isohyetal maps are prepared by interpolating rainfall data recorded at gauged points [1].

A rainfall hyetograph is a plot of rainfall depth or intensity as a function of time, shown in the form of a histogram in figure 7 (a) for the 1-Bee data. By summing the rainfall increments through time, a cumulative rainfall hyetograph, or rainfall mass curve, is produced, as shown in figure 7 (b). The maximum rainfall depth, or intensity, (depth/time) recorded in a given time interval in a storm is found by computing a series of running totals of rainfall depth for that time interval starting at various points in the storm, then selecting the maximum value of this series [1].

Rainfall intensities and their corresponding drop sizes and terminal velocities are given in Table 8 [4]:

Popular Name	Intensity [mm/hr]	Drop diameter [mm]	Terminal velocity [m/sec]
Fog	Trace	0.01	0.003
Mist	0.05	0.10	0.250
Drizzle	0.25	0.20	0.750
Light	1.00	0.45	2.000
Moderate	4.00	1.00	4.000
Heavy	15.00	1.50	5.000
Excessive	40.00	2.10	6.000
Cloudburst	100.00	3.00	8.000

Table 8 Rainfall intensity, drop diameter and terminal velocity [4].

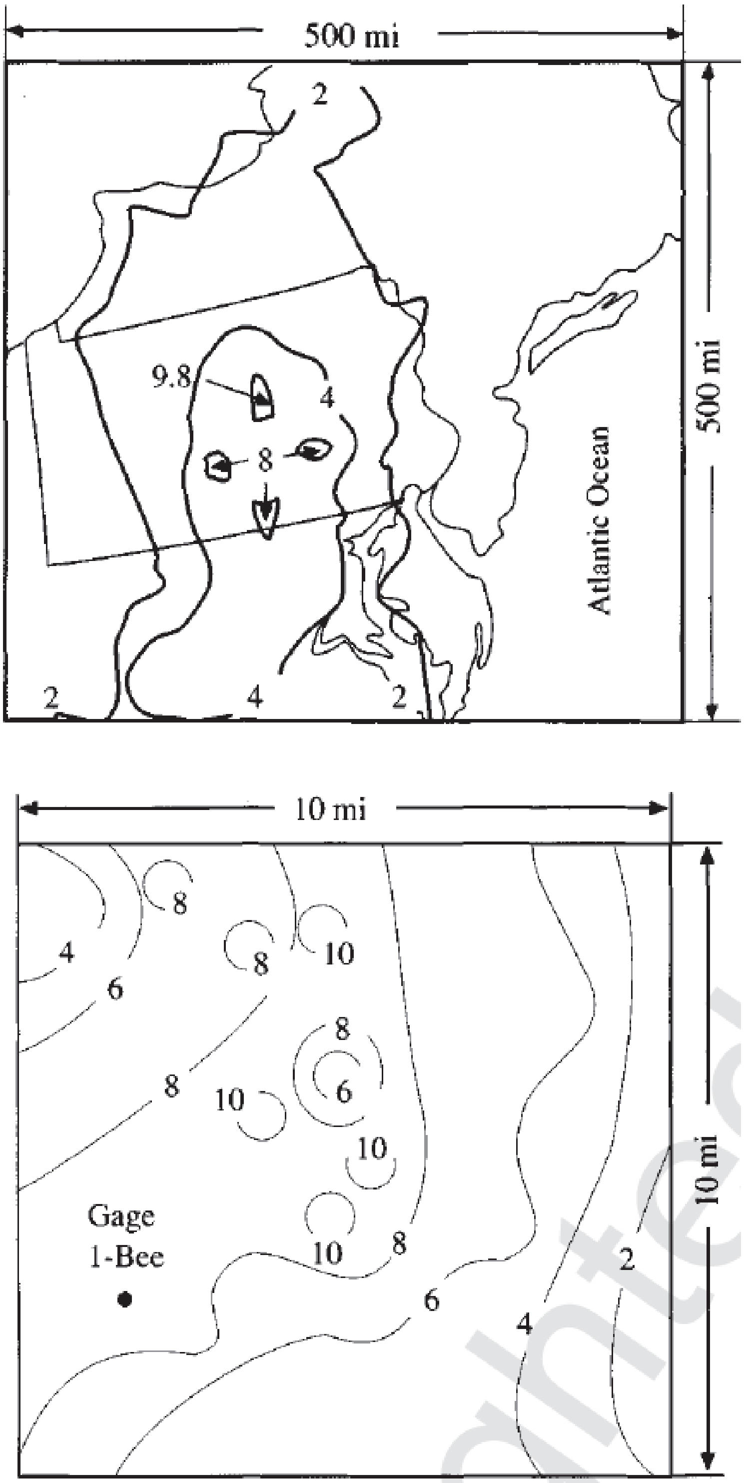


Figure7 Isohyetal maps for two storms. The storms have about the same maximum depth of point rainfall, but the Johnstown storm covered a much larger area and had a longer duration than did the Austin storm [1].

6. STORAGE

The water balance equation, explained in Chapter 1, contains a *storage* term (S).Within the hydrological cycle there are several areas where water can be considered to be stored, most notably soil moisture, groundwater, snow and ice and, to a lesser extent, lakes and reservoirs. It is tempting to see stored water as static, but in reality there is considerable movement involved. With the figure 8 it will be explain the term *storage*, it can be seen that there is an inflow, an outflow and a movement of water between the two. The inflow and outflow do not have to be equal over a time period; if not, then there has been a *change in storage* (ΔS) [3].

Figure 8 Illustration of the storage term used in the water balance equation [3].

The critical point is that at all times there is some water stored, even if it is not the same water throughout a measurement period. This definition of stored water is not perfect as it could include rivers as stored water in addition to groundwater, etc. The distinction is often made on the basis of flow rates (i.e. how quickly the water moves while in storage). There is no critical limit to say when a deep, slow river becomes a lake, and likewise there is no definition of how slow the flow has to be before becoming stored water. It relies on an intuitive judgement that slow flow rates constitute stored water. The importance of stored water is highlighted by the fact that it is by far the largest amount of fresh water in or around planet. The majority of this is either in snow and ice (particularly the polar ice caps) or groundwater [3].

6.1. Water beneath Earth's surface

One way of considering water beneath the earth's surface is to divide it between the saturated and unsaturated zones (as it can be seen in Figure 9). Water in the saturated zone is referred to as groundwater and occurs *beneath* a *water table*. This is also referred to as water in the *phreatic zone* [3].

Water in the unsaturated zone is referred to as soil water and occurs *above* a *water table*. This is sometimes referred to as water in the *vadose zone* [3].

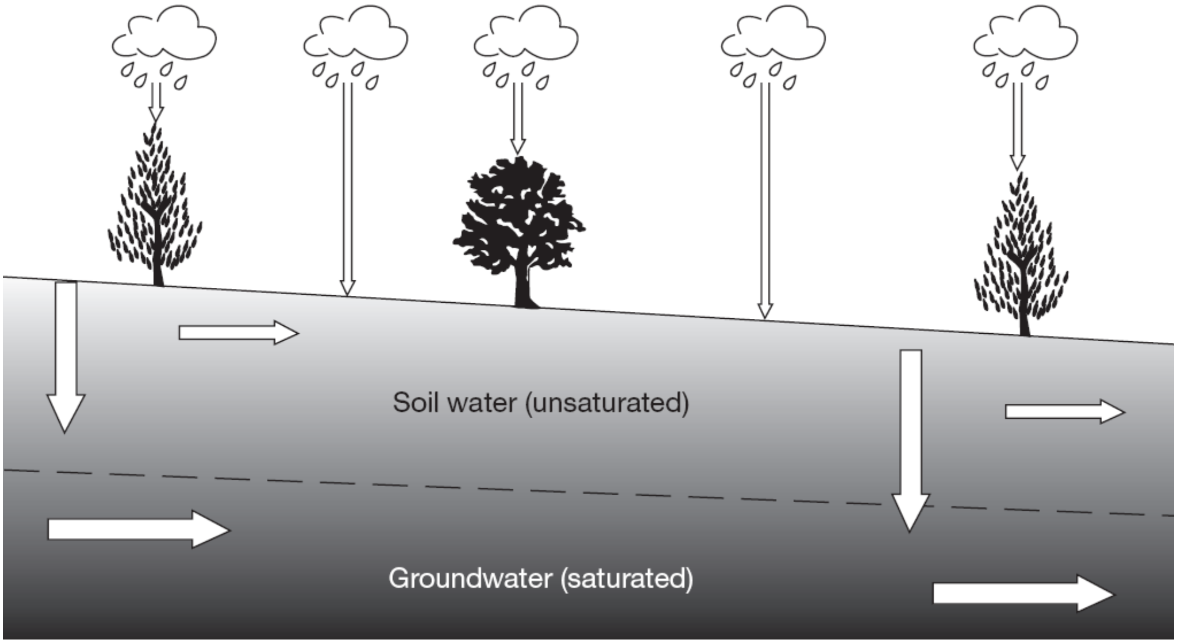


Figure 9 Water stored beneath the earth's surface [3].

As shown in figure 9, rainfall infiltrates through the unsaturated zone towards the saturated zone. The broken line represents the water table, although, as the diagram indicates, this is actually a gradual transition from unsaturated to fully saturated. There is movement of water through both vertical infiltration and horizontal flow. It is important to realize that this occurs in both the unsaturated and saturated zones [3].

6.2. Water in the soil

Soil is essentially a continuum of solid particles (minerals, organic matter), water and air (Figure 10) [10]. Before considering water in the soil, it is necessary to appreciate in more detail the composite mixture of a soil. The functioning of a soil as a water store depends on the packing of the clay or sand particles and the amount of space available between the solids. This pore space may contain gas and/or liquid, which are usually air, water vapour and/or liquid water. The composition of the soil mixture or matrix is described by the relationships of some of the basic properties of the different constituents, these properties are: Density of solids (mean particle density), bulk density of soil, porosity, and void ratio. These simple measures of soil characteristics are important in assessing a soil's water-storage capacity [7].

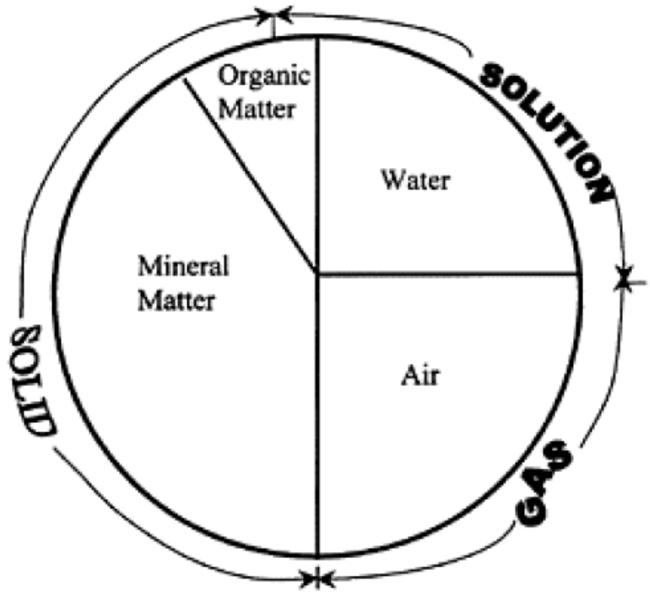


Figure 10 Soil is made up of four components and three phases [10].

Density of solids (mean particle density), in most mineral soils, the mean mass per unit volume of solids is about 2600–2700 kg/m^3. This is close to the density of quartz, which is generally the most prevalent mineral in the coarsest fraction of the soil. Some of the minerals composing the finest fraction of the soil have a similar density [11].

Bulk density of soil is an expression of the total mass of a moist soil per unit volume. As such, this parameter depends more strongly than does the dry bulk density on soil wetness or water content [11].

Porosity is an index of the relative pore space in a soil. Its value generally ranges from 0.3 to 0.6 (30–60%). Coarse-textured soils tend to be less porous than fine-textured soils, though the mean size of individual pores is greater in the former. In clayey soils, the porosity is highly variable because the soil alternately swells, shrinks, aggregates, disperses, compacts, and cracks [11].

The *void ratio* is also an index of the fractional pore space, but it relates that space to the volume of solids rather than to the total volume of the soil. As such, it ranges between 0.3 and 2 [11].

Most of the water content of a soil comes from rainfall or melting snow, and is shown in figure 11, infiltrating as seepage water moving by gravity and surface tension through the pore spaces. Its pathways are smoothed by a thin film of hygroscopic water on each of the soil particles. The hygroscopic moisture is held tightly by electrostatic forces and is not readily moved by other forces, including plant roots. Below the percolating flow, the voids in the soil are filled with air and/or water vapour. This layer is a zone of aeration where there is a complex mixture of solid particles, liquids and gases. With increase in depth, the aeration zone gives way to a layer of saturated soil where all the pore space is occupied by water. In the saturated capillary zone, the water is held by capillary forces between the soil particles and is at less than atmospheric pressure. At greater depths in this saturated zone the water pressure exceeds atmospheric pressure. The surface over which the pressure equals atmospheric pressure is defined as the water table. The extent of the capillary zone is dependent on the soil composition and packing of the soil particles. It ranges from a few centimeters in a coarse sandy soil to a few meters in a clay soil [7].

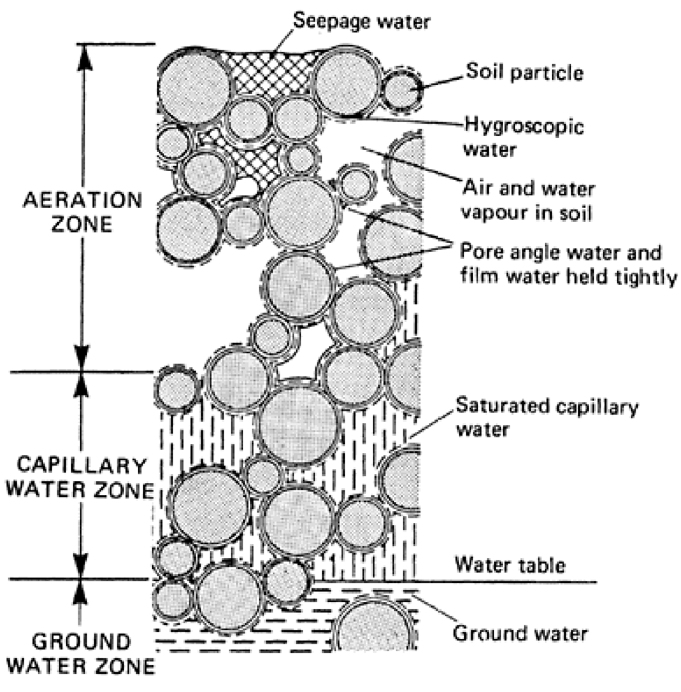


Figure 11 Water in the soil [7].

Soil water content is normally expressed as a *volumetric soil moisture content* or *soil moisture fraction*(θ) [3].

$$\theta = V_w/V_t \tag{3}$$

The soil moisture fraction, θ, is equivalent to the depth ratio of soil water, i.e. the equivalent depth of free water relative to the depth of soil for a unit plan area. In this way, the soil moisture can be related easily to precipitation and evaporation depths. The water content (by volume) is shown for three different soil types for three soil water conditions in Table 9. These data show that there is much less water available at field capacity in a sandy soil that drains quickly. The higher the clay content of a soil, the greater is its retention capability [7].

Soil	Clay content (%)	Saturation	Field capacity	Permanent wilting point
Sand	3	0.40	0.06	0.02
Loam	22	0.50	0.29	0.05
Clay	47	0.60	0.41	0.20

Table 9 Soil Water Content (Volume Fraction θ) [7].

Another way of expressing soil water content is as a *percentage of saturated*. Saturated water content is the maximum amount of water that the soil can hold. Soil water content as percentage of saturated is a useful method of telling how wet the soil actually is. *Field capacity* is the stable point of saturation after rapid drainage [3].

Other terms used in the description of soil moisture content are *soil moisture deficit* and *wilting point*. *Soil moisture deficit* is the amount of water required (in mm depth) to fill the soil up to field capacity. This is an important hydrological parameter as it is often assumed that all rainfall infiltrates into a soil until the moisture content reaches field capacity. The soil moisture deficit gives an indication of how much rain is required before saturation, and therefore when overland flow may occur. *Wilting point* is a term derived from agriculture and refers to the soil water content when plants start to die back (wilt). This is significant for hydrology as beyond this point the plants will no longer transpire [3].

6.3. Water in unsaturated zone

The majority of water in the unsaturated zone is held in soil. Consideration of water in the soil starts with the control over how much water enters a soil during a certain time interval: the infiltration rate. The rate at which water enters a soil is dependent on the current water content of the soil and the ability of a soil to transmit the water [3].

A soil matrix is considered unsaturated when some of the pores are filled with water and the remaining pores with air. The unsaturated zone stores only a tiny fraction of fresh water and, therefore, plays a minor role in the hydrologic cycle. It is the transmission zone, which redistributes the water. Therefore, this zone controls the ground water replenishment as well as evaporation from soil surface. The unsaturated zone experiences transport processes of various kinds, chemical reactions, biological activity of roots, rodents, worms, microbiota, and other organisms. It is also a zone of human activity and is used for the cultivation and disposal of waste. This zone is also drastically disturbed by surface mining and construction of civil structures. The vadose zone is in direct contact with the atmosphere through gaseous fluxes of water vapor and greenhouse gases (CO_2, CH_4, and N_2O) [10].

The fundamental driving forces in both saturated and unsaturated flow are the *potential gradient* and *hydraulic conductivity*. As a stream of water is passed through the unsaturated soil matrix, the incoming water replaces the air present in the soil pores; it increases the total volume of water inside the soil, thus increasing the moisture content (θ) of soil. This agrees with the fundamentals of continuity equation, which states that the difference in the inflow and outflow rate is equal to the change of water storage in soil. The gradient causing flow in unsaturated soils is of negative pressure potential. The flow paths in unsaturated flow are more tortuous as several pores are filled with air. [10].

6.3.1. Capacity to transmit water

The ability of a soil to transmit water is dependent on the pore sizes within it and most importantly on the connections between pores. Pores can be classified according to size or function. Macropores are defined as pores greater than 30 µm (microns) in diameter but can also be defined by their drainage characteristic (the amount of pressure required to remove water from the pore). A well-structured soil consists of stable aggregates with a wide range of pore sizes within and between the aggregates. In this case macropores may make up at least 10 per cent of this soil volume. This structure provides numerous interconnected pathways for the flow of water with a wide range of velocities. In less well-structured soils, biological activity (e.g. roots and worms) can produce macropores that provide flow paths for water that are largely separated from the main soil matrix. The measure of a soil's ability to transmit water is *hydraulic conductivity*. When the soil is wet, water flows through the soil at a rate controlled by the saturated hydraulic conductivity (K_{sat}) [3].

6.3.2. Infiltration rate

This limiting rate of water entry into the profile is known as the *soil infiltration capacity*, and is defined as maximum rate of infiltration into soil. The infiltration rate is the volume flux of water entering through a unit soil surface area. The infiltration rate of a soil depends on texture, structure, antecedent soil moisture content (i.e., the moisture content of soil profile before rainfall or irrigation begins), continuity and stability of pores, and soil matrix potential. With low antecedent moisture content, (e.g., initially dry soil) applied water rapidly enters into the soil matrix. With a continuous supply of water by rainfall or irrigation, the rate of entry of water or infiltration rate decreases over time until it reaches a steady state or a constant rate. The constant rate is also termed as steady state or equilibrium infiltration rate [10].

The rate at which water infiltrates the soil is not constant. Generally, water initially infiltrates at a faster rate and slows down with time (Figure 12) [3].

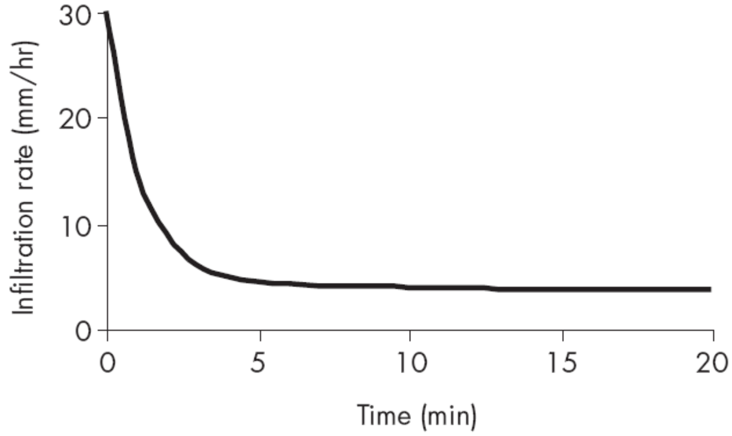


Figure 12 Typical infiltration curve [3].

The infiltration rate of a soil depends on factors that are constant, such as the *soil texture*. It also depends on factors that vary, such as the *soil moisture content*.

- ***Soil Texture***: Coarse textured soils have mainly large particles in between which there are large pores. On the other hand, fine textured soils have mainly small particles in between which there are small pores (Figure 13). In coarse soils, the rain or irrigation water enters and moves more easily into larger pores; it takes less time for the water to infiltrate into the soil. In other words, infiltration rate is higher for coarse textured soils than for fine textured soils. [12].

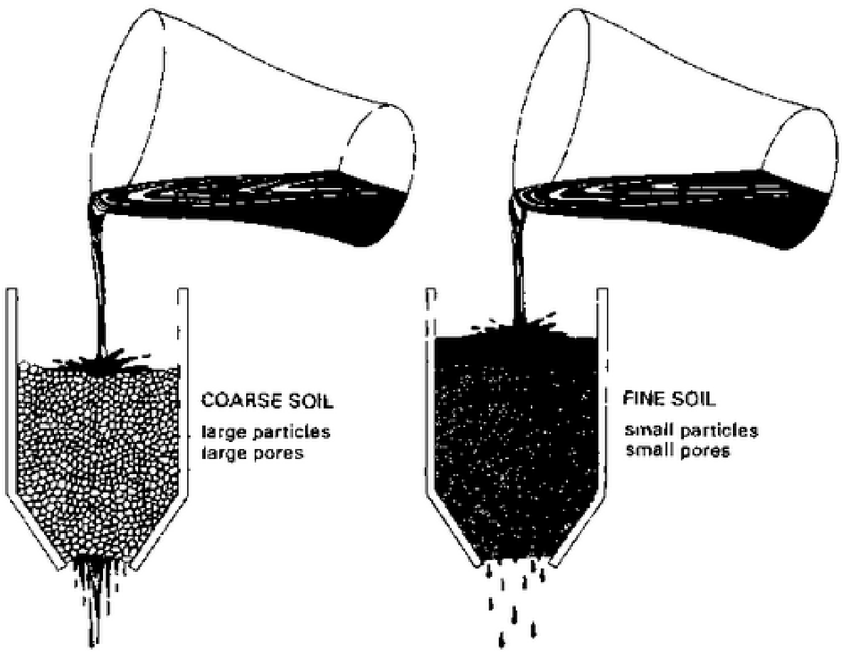


Figure 13 Infiltration rate and soil texture [12].

- ***The soil moisture content:*** The water infiltrates faster (higher infiltration rate) when the soil is dry, than when it is wet. As a consequence, when irrigation water is applied to a field, the water at first infiltrates easily, but as the soil becomes wet, the infiltration rate decreases [12].

- ***The soil structure:*** Generally speaking, water infiltrates quickly (high infiltration rate) into *granular soils* but very slowly (low infiltration rate) into *massive* and *compact soils* [12].

The main force driving infiltration is *gravity*, but it may not be the only force. When soil is very dry it exerts a pulling force that will suck the infiltrating water towards the drier area. With both of these forces the infiltrating water moves down through the soil profile in a wetting front. The wetting front is three-dimensional, as the water moves outwards as well as vertically down [3].

6.4. Water in saturated zone

Once water has infiltrated through the unsaturated zone it reaches the water table and becomes groundwater. This water moves slowly and is not available for evaporation (except through transpiration in deep-rooted plants), consequently it has a long residence time. This may be so long as to provide groundwater reserves available from more pluvial (i.e. greater precipitation) times. It would be wrong to think that all groundwater moves slowly; it is common to see substantial movement of the water and regular replenishment during wetter months. In limestone areas the groundwater can move as underground rivers, although it may take a long time for the water to reach these conduits. In terms of surface hydrology groundwater plays an important part in sustaining streamflows during summer months [3].

An *aquifer* is a layer of unconsolidated or consolidated rock that is able to transmit and store enough water for extraction. Aquifers range in geology from unconsolidated gravels such as the Ogallala aquifer in the USA to distinct geological formations (e.g. chalk underlying London and much of south-east England). An *aquitard* is a geological formation that transmits water at a much slower rate than the aquifer. This is an oddly loose definition, but reflects the fact that an aquitard only becomes so relative to an aquifer. The term aquifuge is sometimes used to refer to a totally impermeable rock formation (i.e. it could never be considered an aquifer) [3].

There are two forms of aquifer that can be seen: *confined* and *unconfined*. A *confined aquifer* has a flow boundary (aquitard) above and below it that constricts the flow of water into a confined area (see Figure 14). Geological formations are the most common form of confined aquifers, and as they often occur as layers the flow of water is restricted in the vertical dimension but not in the horizontal. Water within a confined aquifer is normally under pressure and if intersected by a borehole will rise up higher than the constricted boundary. If the water reaches the earth's surface it is referred to as an artesian well. The level that water rises up to from a confined aquifer is dependent on the amount of fall (or hydraulic head) occurring within the aquifer [3].

An unconfined aquifer has no boundary above it and therefore the water table is free to rise and fall dependent on the amount of water contained in the aquifer (see Figure 15). The lower boundary of the aquifer may be impervious but it is the upper boundary, or water table, that is unconfined and may intersect the surface. It is possible to have a perched water table or perched aquifer (see Figure 14) where an impermeable layer prevents the infiltration of water down to the regional water table. Perched water tables may be temporary features reflecting variable hydraulic conductivities within the soil and rock, or they can be permanent features reflecting the overall geology [3].

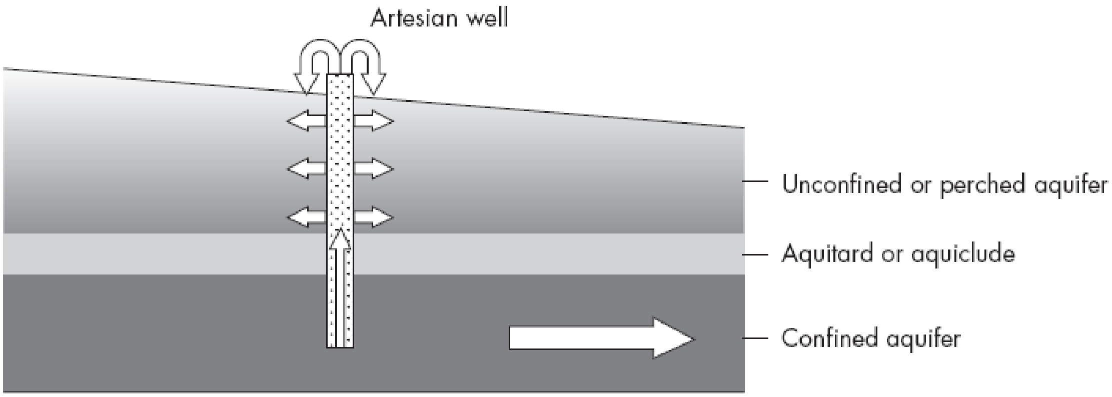


Figure 14 A confined aquifer [3].

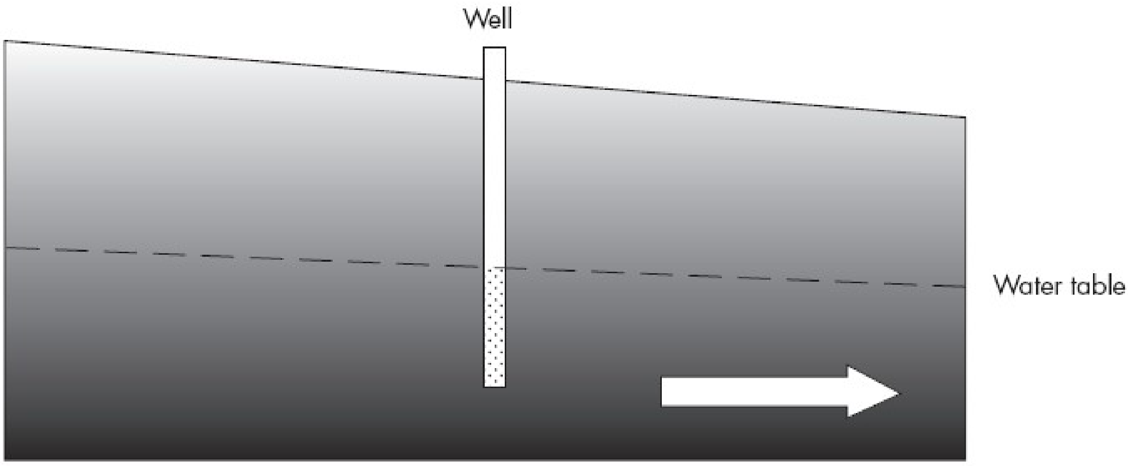


Figure 15 An unconfined aquifer [3].

7. RUNOFF

Runoff is the water leaving a drainage basin, and it is the signature component of the terrestrial branch of the hydrologic cycle. Although runoff represents a residual portion of precipitation remaining after evapotranspiration depletes the moisture supply, runoff is significant because it is the water available for human use. The runoff process traces what happens to precipitation after it arrives at the land surface. In, fact, runoff can be thought of as the integration of complex hydroclimatic processes acting on precipitation after it reaches the surface [10].

A portion of the precipitation seeps into the ground to replenish Earth's groundwater. Most of it flows downhill as runoff. Runoff is extremely important because not only does it keep rivers and lakes full of water, but it also changes the landscape by the action of erosion. Flowing water has tremendous power, it can move boulders and carve out canyons. Runoff of course occurs during storms [8].

Runoff is a loose term that covers the movement of water to a channelized stream, after it has reached the ground as precipitation. The movement can occur either on or below the surface and at differing velocities. Once the water reaches a stream it moves towards the oceans in a channelized form, the process referred to as streamflow or riverflow. Streamflow is expressed as discharge: the volume of water over a defined time period [3].

7.1. Runoff mechanism

Gravity and capillary forces cause the infiltrated water to percolate down to deeper layers or divert laterally from large pores to smaller pores. As pores fill with water, the increase in soil water content causes the decline in soil water deficit and consequently slows down the infiltration rate. Also, the presence of impermeable or semipermeable rocks or clays in the soil profile can block and slow down water movement. Infiltrated water can become surface runoff again as it flows laterally and downslope or routes to nearby stream channels as subsurface runoff [4].

At figure 16 can be recognized the three basic flow types at the hillslope scale. *Overland flow* (Q_o) is the water which runs across the surface of the land before reaching the stream. In the subsurface, *throughflow* (Q_t) occurs in the shallow subsurface, predominantly, although not always, in the unsaturated zone. *Groundwater flow* (Q_G) is in the deeper saturated zone. All of these are runoff mechanisms that contribute to streamflow. The relative importance of each is dependent on the catchment under study and the rainfall characteristics during a storm. [3]

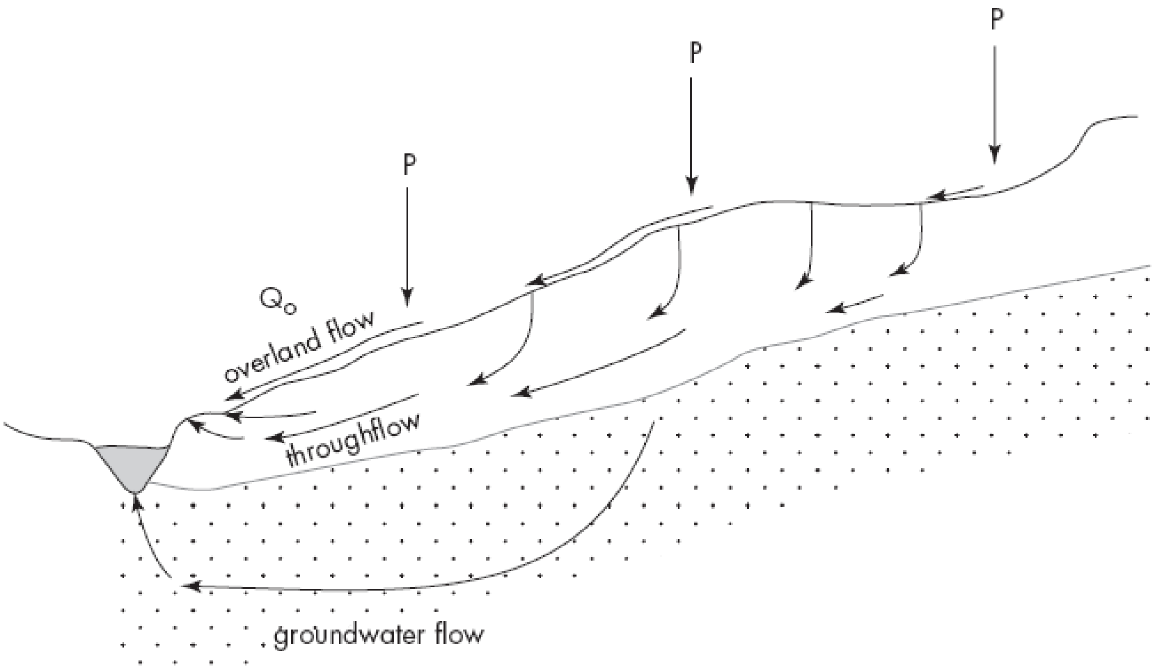


Figure 16 Hillslope runoff processes. [3]

7.1.1. Overland flow

Overland flow is the result of rainfall rates exceeding the infiltration rate of the soil. Depending on soil type, topography, and climatic factors, surface runoff may be generated either as infiltration excess, saturation excess, or as a combination. Infiltration is a major determinant of how much rainfall becomes runoff [13].

Robert Horton (1875–1945) ecologist who made the first detailed studies about how occurs the overland flow, hypothesized that happened when the rainfall rate was higher than the infiltration rate of a soil. Horton went on to suggest that under these circumstances the excess rainfall collected on the surface before travelling towards the stream as a thin sheet of water moving across the surface. Under this hypothesis it is the infiltration rate of a soil that acts as a controlling barrier or partitioning device. Where the infiltration capacity of a soil is low, overland flow occurs readily. This type of overland flow is referred to as *infiltration excess* overland flow or *Hortonian overland flow* [3].

Saturation excess runoff is common in mountainous terrain or watersheds with highly porous surface. Under these conditions, overland flow may not be observed. Runoff occurs by infiltrating to a shallow water table. As the gradient of the water table increases, runoff to stream channels also increases. As the water table surface intersects the ground surface areas adjacent to the stream channel, the surface saturates. The saturation zone grows in areal extent and rain falls on this area, more runoff occurs [13].

Surface runoff is responsible for producing quick streamflow discharge. However, forested watersheds usually have little surface runoff.

7.1.2. Subsurface flow

Under the variable source areas concept there are places within a catchment that contribute overland flow to the storm hydrograph. When we total up the amount of water found in a storm hydrograph it is difficult to believe that it has all come from overland flow, especially when this is confined to a relatively small part of the catchment (i.e. variable source areas concept). The manner in which the recession limb of a hydrograph attenuates the storm flow suggests that it may be derived from a slower movement of water: subsurface flow. In addition to this, tracer studies looking at where the water has been before entering the stream as storm flow have found that a large amount of the storm hydrograph consists of *old water*. This old water has been sitting in the soil, or as fully saturated groundwater, for considerable length of time and yet enters the stream during a storm event. There have been several theories that involve throughflow and groundwater as explanation of these findings [3].

a. Throughflow

Throughflow is a general term used to describe the movement of water through the unsaturated zone; normally this is the soil matrix. Once water infiltrates the soil surface it continues to move, either through the soil matrix or along preferential flow paths (referred to as lateral or preferential flow). The rate of soil water movement through a saturated soil matrix is described by Darcy's law. Under normal, vertical, infiltration conditions the hydraulic gradient has a value of -1 and the saturated hydraulic conductivity is the infiltration capacity. Once the soil is saturated the movement of water is not only vertical. With a sloping water table on a hillsope, water moves down slope. In order for throughflow to contribute to storm runoff there must be another mechanism (other than matrix flow) operating [3].

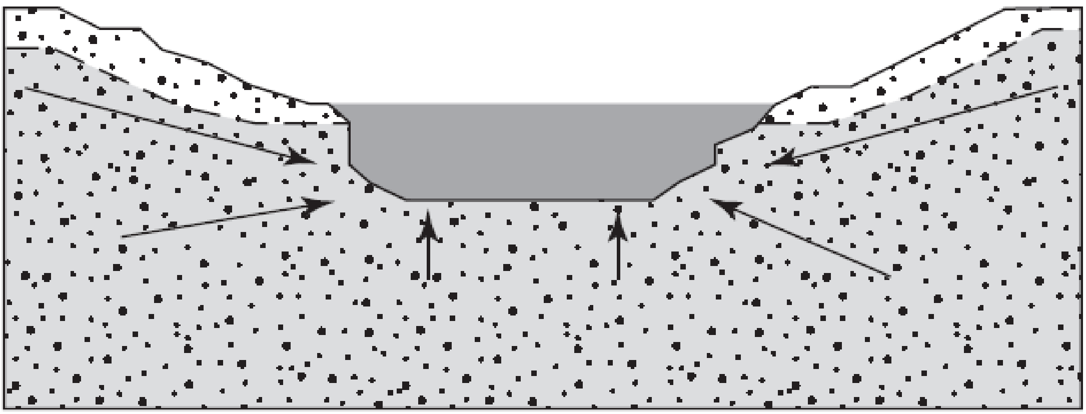
b. Groundwater flow

The movement of water that flows and drains through soil and rock underground it is called *groundwater flow*. Confined groundwater is under a lot of pressure, stored in cavities and geologic pores of the earth's crust. Unconfined groundwater is the term for an aquifer with an exposed water surface. Water flows across a land surface then penetrates soil and rock. Once it goes underground, the water is still moving. Groundwater flow speed depends on subsurface materials and the amount of water. From the land surface, the water moves to the water table [5].

Base flow is water that has infiltrated the soil surface and moved towards the saturated zone. Once in the saturated zone it moves downslope, often towards a stream. A stream or lake is often thought to occur where the regional water table intersects the surface, although this may not always be the case. However in general it can be said that baseflow is provided by the slow seepage of water from groundwater into streams. This will not necessarily be visible (e.g. springs) but can occur over a length of streambank and bed and is only detectable through repeated measurement of streamflow down a reach [3].

The interaction between groundwater and streamflow is complex and depends very much on local circumstances. Water naturally moves towards areas where faster flow is available and consequently can be drawn upwards towards a stream. This is the case in dry environments but is dependent on there being an unconfined aquifer near to the surface. If this is not the case then the stream may be contributing water to the ground through infiltration. Figure 17 shows two different circumstances of interaction between the groundwater and stream. In Figure 17 (a) the groundwater is contributing water to the streamflow as the water table is high. In Figure 17 (b) the water table is low and the stream is contributing water to the groundwater. This is commonly the case where the main river source may be mountains a considerable distance away and the river flows over an alluvial plain with the regional groundwater table considerably deeper than stream level [3].

(a)



(b)

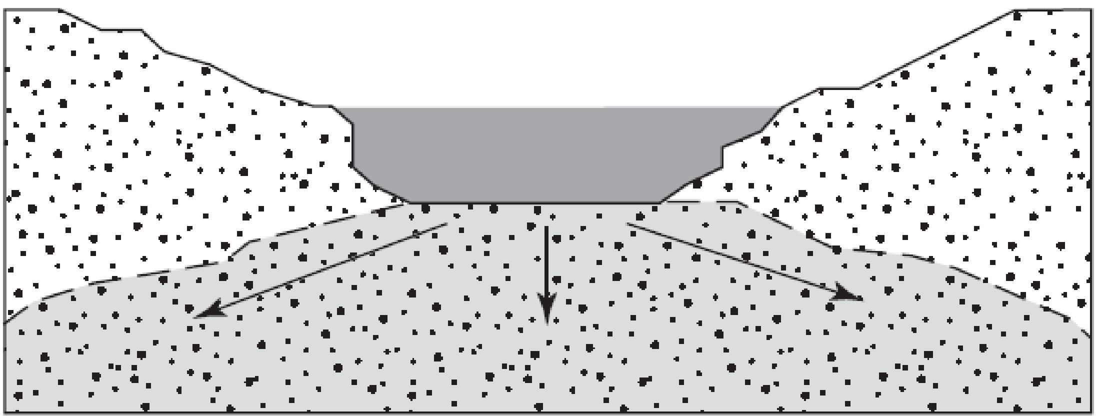


Figure 17 The interactions between a river and the groundwater. In (a) the groundwater is contributing to the stream, while in (b) the opposite is occurring [3].

7.1.3. Channel flow

Once water reaches the stream it will flow through a channel network to the main river. The controls over the rate of flow of water in a channel are to do with the volume of water present, the gradient of the channel, and the resistance to flow experienced at the channel bed. The resistance to flow is governed by the character of the bed surface. Boulders and vegetation will create a large amount of friction, slowing the water down as it passes over the bed. In many areas of the world the channel network is highly variable in time and space. Small channels may be ephemeral and in arid regions will frequently only flow during flood events. The resistance to flow under these circumstances is complicated by the infiltration that will be occurring at the water front and bed surface. The first flush of water will infiltrate at a much higher rate as it fills the available pore space in the soil/rock at the bed surface. This will remove water from the stream and also slow the water front down as it creates a greater friction surface. Under a continual flow regime the infiltration from the stream to ground will depend on the hydraulic gradient and the infiltration capacity [3].

7.2. Factors affecting runoff

It is generally recognized that runoff from a given watershed is influenced by two major groups of factors categorized as climatic and physiographic [14].

7.2.1. Climatic factors

The climatic factors of the watershed affecting the runoff are mainly associated with the characteristics of precipitation, which include [14]:

- **Type of precipitation:** Types of precipitation have a great effect on the runoff. For example a precipitation which occurs in form of rainfall, starts immediately in form of surface flow (surface runoff) over the land surface depending upon its intensity as well as magnitude, while a precipitation which takes place in form of snow or hails the flow of water on ground surface will not take place immediately, but after melting of the same. During the time interval of their melting the melted water infiltrates into the soil and results a very little surface runoff generation [14].

- **Rainfall intensity:** The intensity of rainfall has a dominating effect on runoff yield. If rainfall intensity is greater than infiltration rate of the soil the surface runoff takes place very shortly while in case of low intensity rainfall, where is found a reverse trend of the same. Thus high intensities of rainfall yield higher runoff and vice-versa [14].

- **Duration of rainfall:** Rainfall duration is directly related to the volume of runoff due the fact, that infiltration rate of the soil decreases with the duration of rainfall till it attains constant rate. As a result of this, even a mild intensity rainfall lasting for longer duration may yield a cover durable amount of runoff [14].

- **Rainfall distribution:** Runoff from a watershed depends very much on the distribution of rainfall. The rainfall distribution for this purpose can be expressed by a term "distribution coefficient" which may be defined as the ratio of maximum rainfall at a point to the mean rainfall of the watershed. For a given total rainfall, if all other conditions are the same, the greater the value of distribution coefficient, greater will be the peak runoff and vice - versa. However, for the same distribution coefficient, the peak runoff would be resulted from the storm, falling on the lower part of the basin i.e. near the outlet [14].

- **Direction of prevailing wind:** The direction of prevailing wind, affected greatly the runoff flow. If the direction of prevailing wind is same as the drainage system then it has great influence on the resulting peak flow and also on the duration of surface flow, to reach at the outlet. A storm moving in the direction of stream slope produces a higher peak in shorter period of time than a storm moving in opposite direction [14].

- **Other climatic factors:** such as temperature, wind velocity, relative humidity, annual rainfall etc. affect the water losses from the watershed area to a great extent and thus the runoff is also affecter accordingly. If the losses are more the runoff will be less and vice –versa [14].

7.2.2. Physiographic factors affecting runoff

Physiographic factors of watershed consist of both, the watershed and the channel characteristics. The different characteristics of watershed and channel, which affect the runoff, are listed below.

- **Topographic Characteristics:** these include more topographical features of watershed which create their effect on runoff it is mainly undulating nature of the reason that runoff water gets additional power to flow due to slope of the surface and altitude time to infiltrate the water into solid. Regarding channel characteristics to describe their effect on runoff the channel cross-section, roughness storage and channel density are mainly considered. These also have significant effect on runoff [14].

Watershed topography can be characterized by a variety of parameters such as slope, shape, elevation, size, relief ratio, stream density and frequency, and many others. They affect streamflow and influence the shape of the hydrograph through watershed storage, runoff speed, infiltration, and soil water content. A watershed with higher elevations implies lower temperature, less evapotranspiration, greater rainfall, steeper slope, and shallower soil depth, which lead to produce more runoff. A steep slope can make overland runoff greater and faster and soil infiltration lower [4].

The hydrologic behavior of small watersheds tends to be different from that of large watersheds. A small watershed is very sensitive to high-intensity rainfall of short duration and land use. Thus, overland flow is a dominating factor affecting the peakflow, and the streamflow hydrograph is characterized by a sharp rise to peakflow and a rapid fall in recession. In large watersheds, the average watershed slope, chances for a single storm to cover the entire watershed, and the average storm depth and intensity are smaller. Thus, the streamflow hydrograph is dominated by watershed and channel storage, and it exhibits a broader crest and longer time base [4].

- **Land use:** Plant cover, through the unique effects of its canopy and root systems on precipitation interception, infiltration, percolation, surface detention and roughness, transpiration, snow accumulation, and snowmelt, is a very important factor in the hydrologic cycle. Forest cutting usually results in an increase in water yield. The increase is most significant if the cutting is conducted in watersheds with conifer species, followed by hardwoods, chaparrals, and grasses. A forested watershed is expected to produce a hydrograph with lower peakflow, smaller volume of runoff, and broader time base than if the watershed had been cleared, cultivated, and pastured [4].

- **Size of watershed:** Regarding the size of watershed, if all other factor including depth and intensity of rainfall are being same them two watershed irrespective of their size, will produce about the same amount of runoff .However a large watershed takes longer time for raining the runoff to the outlet as result the peak flow expressed are depth is being smaller and vice versa [14].

- **Shape of watershed:** The shape of watershed has a great effect of runoff. The watershed shape is generally expressed by the terms "from factor and "compactness coefficient" [14].

- **Slope of watershed:** The slope of the watershed has an important role over runoff but its effect is complex. It controls the time of overland flow and time of concentration of rainfall in the drainage channel which provide accumulative effect on resulting peak runoff. For example in case of a sloppy watershed, the time to reach the flow at outlet is less, because of greater runoff velocity which results into formation of peak runoff very soon and vice –versa [14].

- **Orientation of watershed:** This factor affects the evaporation and transpiration losses from the area by making influence on the amount of heat to the received from the sun. The north or south orientation of watershed, affects the time of melting of collected snow. In a mountainous watershed the part of wind ward side of the mountain receives high intensity of rainfall resulting into more runoff yield while the part of watershed typing towards leeward side has reverse find of the same [14].

- **Soil Moisture:** The magnitude of runoff yield depends on the amount of moisture present in the soil at the time of rainfall. If rain occurs over the soil which has more moisture the infiltration rate becomes very less which results in more runoff yield. Similarly if the rain occurs after a long dry spell of time when the soil is dry, causing to absorb huge amount of rain water. In on the other hand, if the rain occurs in a close succession as in the rainy season; runoff yield has reverse effect [14].

- **Soil Type:** In the watershed surface runoff is greatly influenced by the soil type as loose of water from the soil is very much dependent on infiltration rate which varies with the types of soil [14].

7.3. Floods

In a river a flood is normally considered to be an inundation of land adjacent to a river caused by a period of abnormally large discharge or encroachment by the sea. but this definition is fraught with inaccuracy. Flooding may occur from sources other than rivers (e.g. the sea and lakes), and „abnormal" is difficult to pin down, particularly within a timeframe. Floods come to our attention through the amount of damage that they cause and for this reason they are often rated on a cost basis rather than on hydrological criteria. Hydrological and monetary assessments of flooding often differ markedly because the economic valuation is highly dependent on location. If the area of land inundated by a flooding river is in an expensive region with large infrastructure then the cost will be considerably higher than, say, for agricultural land [3].

The extent and size of the flood can often be related to other contributing factors that increase the effect of high rainfall. The largest influence on the size of a flood, apart from the amount and intensity of rainfall, is the wetness of the soil immediately prior to the rainfall or snow melt occurring. The amount of infiltration into a soil and subsequent storm runoff are highly dependent on the degree of saturation in the soil. Almost all major flood events are heavily influenced by the amount of rainfall that has occurred prior to the actual flood-causing rainfall. There is also considerable evidence that a large vegetation cover, such as forest, decreases the severity of flooding. There are several reasons for this, in that trees provide an intercepting layer for rainfall and therefore slow down the rate at which the water reaches the surface. This will lessen the amount of rainfall available for soil moisture and therefore the antecedent soil moisture may be lower under forest than for an adjoining pasture. The other factor is that forests often have a high organic matter in the upper soil layers which, is able to absorb more water. Again this lessens the amount of overland flow, although it may increase the amount of throughflow. Finally, the infiltration rates under forest soils are often higher, leading again to less saturation excess overland flow. The removal of forests from a catchment area will increase the propensity for a river to flood and also increase the severity of a flood event. Conversely the planting of forests on a catchment area will decrease the frequency and magnitude of flood events. In recent years any flooding event has led to a clamor of calls to explain the event in terms of climatic change. This is not easy to do as climate is naturally so variable. What can be said though is that river channels slowly adjust to changes in flow regime which may in turn be influenced by changes in climate. Many studies have suggested that future climate change will involve greater extremes of weather, including more high intensity rainfall events. This is likely to lead to an increase in flooding, particularly while a channel adjusts to the differing flow regime [3].

8. CONCLUSION

The present thesis work has discussed the different process that integrates the water balance equation in the most fundamental form; *precipitation*, *evaporation*, *changes in storage* and *runoff*. Also, describes the different factors affecting such processes and the relationship between them.

Temperature, *wind speed* and *humidity* are factors that most affect evaporation process. The high temperature in the evaporating water as well as in the air will accelerate the evaporation, because the air can hold more water vapour when it has high temperature; if fresh air is moving over the surface all the time, the concentration of the water in the air will have less probability to come up with time, thus encouraging faster evaporation. This results in a boundary layer on the surface of evaporation that decreases with flow rate, decreasing the diffusion distance in the stagnant layer. When the air above the evaporating surface becomes more humid as water evaporates, there comes a point that is saturated and cannot hold more vapour but if the air is moving, the amount of evaporation increments as drier air substitutes the humid air. Temperature also affects the intensity of rainfall, because with high temperatures, the atmosphere will hold more water vapour and this will makes rainfall with more intensity.

Runoff consists of three important flows; these are *overland flow, throughflow* and *groundwater flow.* In runoff process, have an important role the physiographic and climatic factors. Among the physiographic factors it may be mentioned the topographic characteristics of the watershed. For example, water that reaches the ground as precipitation runoff faster and more abundant on a watershed with steeper slope than on a watershed with gentle slope. Also the watershed with higher elevations tends to produce more runoff due to the low temperatures, more abundant rainfall and shallower soil depth.

BIBLIOGRAPHY

[1] CHOW, Ven Te; MAIDMENT, David R.; MAYS, Larry W.: *Applied hydrology.* New York, 1988. 585 pp. ISBN 0-07-100174-3.

[2] SUBRAMANYA, K.: *Engineering hydrology*. Third edition. New Delhi, 2008. 428 pp. ISBN 0-07-064855-7.

[3] DAVIE, Tim: *Fundamentals of hydrology*. Second edition. United States of America, 2002. 195 pp. ISBN 0-203-93366-4.

[4] CHANG, Mingteh: *Forest hydrology: An introduction to water and forests*. United States of America, 2003. 392 pp. ISBN 0-8493-1363-5.

[5] CHADDE, Joan: *Water quality: The watershed concept* [online]. Michigan Environmental Education Curriculum, United States of America. Updated 03.02.2006 [cit. 06.06.2011]. Available at WWW: <http://techalive.mtu.edu/meec/module01/Infiltration.htm>.

[6] FETTER, Charles Willard: *Applied hydrology.* Fourth edition. United States of America, 2000. 598 pp. ISBN 0-13-088239-9.

[7] SHAW, Elizabeth M.: *Hydrology in practice*. Third Edition. United States of America, 1994. 592 pp. ISBN 0-7487-4448-7.

[8] REDDY, Jaya Rami: *Textbook of Hydrology*. New Delhi, 2005. 530 pp. ISBN 8-17-008099-1.

[9] MCCUEN, Richard H.: *Hydrologic analysis and design*. Second edition. United States of America, 1998. 814 pp. ISBN 0-13-134758-7.

[10] LAL, Rattan; SHUKLA, Manoj K.: *Principles of soil physics*. United States of America, 2004. 528 pp. ISBN 0-8247-5324-0.

[11] HILLEL, Daniel: *Introduction to environmental soil physics*. United States of America, 2004. 494 pp. ISBN 0-12-348655-6.

[12] CRITCHLEY, Will; SIEGERT, Klaus: *Water harvesting* [online]. Rome, 1991. [cit. 08.07.2011]. Available at WWW: <http://www.samsamwater.com/library/Water_harvesting_-_Critchley.pdf>.

[13] VIEUX, Baxter E.: *Distributed hydrologic modeling using GIS*. Second edition. United States of America, 2004. 311 pp. ISBN 1-4020-2459-2.

[14] WWW: < http://agriinfo.in/?page=topic&superid=1&topicid=439>

LIST OF FIGURES

LIST OF TABLES